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DRAFT: October 3, 1995

*Guide to Monitoring Releases of Airborne
Radioactive Substances from the Ducts
and Stacks of Nuclear Facilities*

American National Standard
Guide to Monitoring Releases of Airborne Radioactive Substances from the Ducts and Stacks of Nuclear Facilities

Sponsor

Health Physics Society

Approved

American National Standards Institute, Inc.

Abstract

American National Standard N13.1 sets forth guidelines and performance criteria for monitoring the emissions of airborne radioactive substances in the air discharge ducts and stacks of nuclear facilities. Emphasis is on extractive sampling from a location in a stack or duct where the contaminant is well mixed. At such a location, sampling may be conducted at a single point. This standard provides performance based criteria for the use of air sampling probes, transport lines, sample collectors, sample monitoring instruments, and gas flow measuring methods. This standard also covers sampling program objectives, quality assurance issues, developing air monitoring control action levels, system optimization, and system performance verification. Workplace, containment, or environmental air monitoring are not addressed. Specific sample analysis methods and the reporting or interpreting of results are also not addressed.

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Foreword (This foreword is not part of American National Standard N13.1-1995.)

Monitoring releases of airborne radioactive substances from the ducts and stacks of nuclear facilities is important for operating safety, public safety, and the protection of the environment. It frequently provides operating personnel with the first indication of changing conditions, and it provides supervisory personnel and public safety officials with factual information about the amount and nature of the releases to enable them to decide on appropriate protective and corrective actions. Consequently, exhaust air monitoring is generally required by regulatory agencies whenever radioactive materials are present in significant quantities, and there is a possibility that some of these materials could be released to the atmosphere.

Exhaust air monitoring is complicated by the fact that the radioactive substances may be in the form of solid aerosols, liquid aerosols, condensible vapors, and gases; and by the fact that the monitoring equipment must operate continuously with little attention and with a high degree of reliability. Another complication is the large size of the aerosol particles (up to 100 micrometers) that may be released in the event of an exhaust filter failure[1,2]. Although particles of this size are not likely to cause a respiratory problem, they may produce human exposures through indirect pathways such as the ingestion of meat or milk from cows that have eaten contaminated grass.

There are numerous reasons for revising the 1969 version of ANSI N13,1 "Guide to Sampling Airborne Radioactive Materials in Nuclear Facilities," which is now obsolete. These reasons include the following:

- Monitoring airborne releases from ducts and stacks is sufficiently different from other kinds of air sampling that it deserves to be the subject of a separate Standard;

- Appendix A of the 1969 Standard "Guides for Sampling from Ducts and Stacks" led to faulty systems that did not minimize sampling errors and obtain meaningful results;

- There have been enormous advances in aerosol science since 1969;

- Experimental and theoretical evidence has shown that extractive sampling from a well-mixed stream with a properly designed nozzle is the most effective way to provide a representative sample;

- The new Standard includes numerical performance criteria as well as guidelines on acceptable performance for monitoring aerosols, condensible

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[1] See "Some Experience with Measurements of Stack Releases and their Correlation with Environmental Measurements" by J. Czarnecki in Radiation Protection Practice, Vol. II, Pergamon Press, 1988.

[2] Also see "The Measurement of Power Reactor Stack Releases Under Accident Conditions" by L. Ström in NS-89/18, 1989, Studsvik AB, S-61182 Nyköping, Sweden.

vapors, and gases to provide a quantitative basis for system design and system acceptance testing, and to help stimulate research on ways of achieving the needed levels of performance;

- Duct and stack monitoring systems must be tested periodically like other emergency equipment, and must be kept in a state of readiness for the occurrence of unplanned releases[3].

There are nine annexes in this standard, all of which are informative and are not considered part of this standard.

Suggestions for improvement of this standard are welcome and will be considered for subsequent revisions. All comments and suggestions should be sent to John Glissmeyer, Battelle Pacific Northwest Laboratory, P.O. Box 999, Richland, Washington 99352.

The Standards Committee on Radiation Protection which reviewed and approved this standard, had the following personnel at the time of approval:

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[3] See "Performance Evaluation of the Air Exhaust Sampling and Monitoring Systems at the Bruce-A Nuclear Generating Station" by K.E. Curtis and A. Guest in Proceedings of the 19th DOE/NRC Nuclear Air Cleaning Conference, 1986.

American National Standard
Guide to Monitoring Releases of Airborne Radioactive Substances from the Ducts and Stacks of Nuclear Facilities

0 Introduction

ANSI N13.1 was first issued in 1969 as a guide to sampling airborne radioactive materials in the ducts, stacks, workplaces and environs of installations where work with radioactive materials is conducted. Since then, an improved technical basis has been developed for each of the major sampling specialties. Consequently, the scope of the revised ANSI N13.1 has been narrowed to directed airflow situations such as ducts and stacks.

This standard presents a new approach to representative sampling. The goal of achieving an unbiased, representative sample is accomplished by requiring that samples are extracted from airstreams meeting rigorous criteria for being well mixed for potential airborne contaminants. This standard sets forth guidelines and performance criteria for the proper use of air sampling nozzles, transport lines, sample collection and monitoring devices, and gas flow measuring methods in obtaining valid measurements of airborne radioactive materials in ducts or stacks. The guidelines and criteria presented in this standard are covered in the following clauses:

Clause 3 provides a glossary and nomenclature used in this standard to define terms and symbols that are used in the equations.

Clause 4 covers the objectives and approaches for sampling programs.

Clause 5 discusses the requirements for selecting sampling locations.

Clause 6 covers the requirements for designing the sampling system components.

Clause 7 describes the requirements of an acceptable quality assurance program specific for air sampling.

In addition, the following annexes provide information of use to sampling program and system designers:

Annex A provides techniques for measurement of flowrate through a stack or duct.

Annex B outlines modeling of particle losses in transport systems and presents an example of using a computer code to estimate aerosol penetration through a transport system.

Annex C presents special considerations for the extraction, transport and sampling of radioiodine.

1   *Annex D* illustrates criteria for the selection of filters for collecting airborne radioactive particles.

2

3   *Annex E* describes the statistical basis of evaluating effluent sampling errors and uncertainty.

4

5   *Annex F* summarizes when to conduct sampling system performance verification and how this may
6   be accomplished.

7

8   *Annex G* explains transuranic aerosol particulate characteristics and the implications for extractive
9   sampling in nuclear facility effluents.

10

11   *Annex H* discusses tritium sampling and detection.

12

13   This standard does not cover:

14

15   — determining sampling locations in work areas or containments;
16   — selecting specific instrumentation for sample collection or on-line monitoring of collected
17   samples;
18   — analyzing collected samples;
19   — reporting and interpreting results.

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21

22   **1 Scope**

23

24   This standard sets forth guidelines and performance-based criteria for the design and use of
25   systems for monitoring the releases of airborne radioactive substances from the ducts and stacks of
26   nuclear facilities.

27

28   **1.1 Relationship to other standards**

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30   The potential applications of this standard are diverse, and consequently it is inappropriate to incor-
31   porate the many laws, regulations, and guidelines of governmental bodies that have an interest in
32   the measurement of radioactive air emissions. It is incumbent on the user to be familiar with the
33   applicable regulations.

34

35   **1.2 Application of this standard**

36

37   The requirements presented in this standard are aimed at sampling programs conducted for regu-
38   latory compliance. These requirements may not be universally applicable to all sampling programs,
39   especially those with more limited objectives such as process control. When designing systems
40   with objectives other than regulatory compliance, the designer should exercise professional
41   judgement in the application of these requirements and should explicitly document the sampling
42   objectives and the reasons for any exceptions to the requirements of this standard.

43

44

45   **2 Normative references**

46

47   The following standards and U.S. Environmental Protection Agency (EPA) test methods contain
48   provisions that, through reference in this text, constitute provisions of this American National
49   Standard. At the time of publication, the editions indicated were valid. All standards and EPA
50   methods are subject to revision, and parties to agreements based on this American National
51   Standard are encouraged to investigate the possibility of applying the most recent editions of the
52   standards and methods indicated below.

1   ANSI N13.2-1969 (Reaffirmed 1982), *Administrative Practices in Radiation Monitoring*, outlines
2   administrative practices of a program for monitoring ionizing radiation, including gaseous effluents.
3

4   ANSI N42.18-1980 (Reaffirmed 1991, formerly ANSI N13.10), *Specification and Performance of*
5   *On-site Instrumentation for Continuously Monitoring Radioactivity in Effluents*, provides performance
6   criteria for instrumentation used for monitoring radioactivity in liquid and airborne effluent streams.
7   How effluent stream characteristics, operating environment factors, and standards and regulations
8   affect the selection of instrumentation for effluent monitoring systems are briefly discussed.
9   Dynamic range; sensitivity; accuracy; precision, physical, mechanical and electrical requirements;
10 and detection capability are also addressed. Testing procedures are not covered.
11

12 ANSI N320 (1979), *Performance Specifications for Reactor Emergency Radiological Monitoring*
13 *Instrumentation*, addresses the essential performance parameters of monitoring instruments used
14 during an accident event at reactors. The instrument operating environment, operational character-
15 istics, lower and upper detection limits are also addressed. The general instrument locations inside
16 the reactor plant, at release points, and in the plant environs are addressed.
17

18 ANSI/ASME Performance Test Code (PTC) 38-1980, *Determining the Concentration of Particulate*
19 *Matter in a Gas Stream*, is oriented toward short term measurements of combustion product
20 streams, but contains useful information on sample flowmeters and characterizing gas flows in a
21 duct or stack. This code served as a basis for the EPA Test Methods.
22

23 40 CFR 60, Appendix A, *Method 1 - Sample and Velocity Traverses for Stationary Sources*,
24 provides criteria for the number of points and conditions for velocity measurements.
25

26 40 CFR 60, Appendix A, *Method 1A - Sample and Velocity Traverses for Stationary Sources With*
27 *Small Stacks or Ducts*, provides criteria for velocity mapping in stacks or ducts that are less than
28 300 mm in diameter.
29

30 40 CFR 60, Appendix A, Method 2, *Determination of Stack Gas Velocity and Volumetric Flowrate*
31 *(Type S Pitot Tube)*, provides a methodology for flow measurements.
32

33 40 CFR 60, Appendix A, Method 2C, *Determination of Stack Gas Velocity and Volumetric Flowrate*
34 *in Small Stacks or Ducts (Standard Pitot Tube)*, describes flow characterization methodology for
35 stacks and ducts less than 300 mm in diameter.
36

37 40 CFR 60, Appendix A, *Method 5 - Determination of Particulate Emissions From Stationary*
38 *Sources*, provides a method for periodic extractive sampling.
39

40 40 CFR 60, Appendix A, *Method 17 - Determination of Particulate Emissions From Stationary*
41 *Sources (In-stack Filtration Method)*, describes a method for periodic sampling with filter holder
42 located close to the nozzle in the stack.
43
44

45 **3 Glossary and nomenclature**
46

47 A system for sampling radionuclides from a stack or duct can consist of several general components
48 as shown in figures 1a and 1b. A nozzle, placed at a location where a representative sample can be
49 extracted, is used to remove the sample from the bulk flow stream. The transport line generally
50 consists of tubing and connectors. Connectors can be bends,

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Stack or Duct

Transport System

Transport Line (excludes nozzle)

Conditioning System (not needed in most applications)

Collector or Monitor

Flow Meter and Vacuum Source

Nozzle

Flow

Discharge

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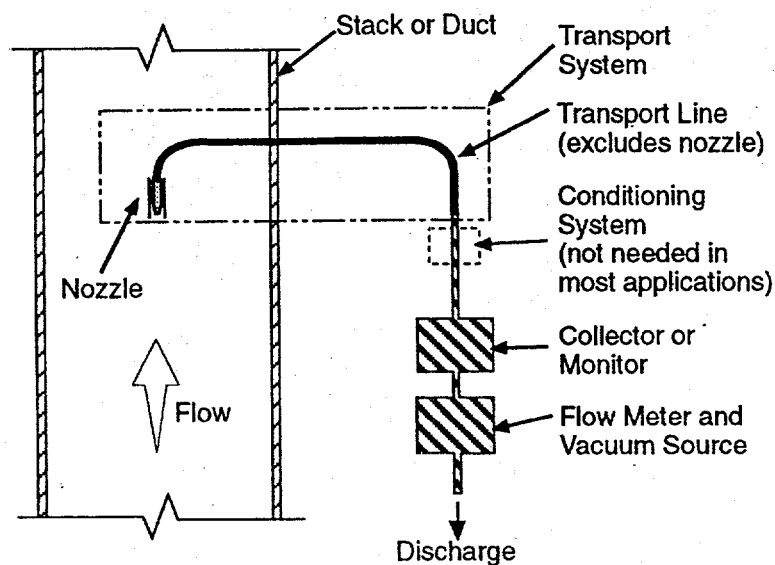
Figure 1a — Generic sampling system. Flow schematic where components are identified.

Sampling or Monitoring System

Transport System

Conditioning System

Collection or Monitor

Flow System

Nozzle

Transport Line

—Diluters
—Concentrators
—Humidifiers
—Driers
—Diffusion Denuders

—Continuous Air Monitor
—Filter
—Absorbent
—Adsorbent

—Vacuum Source
—Metering
—Controls
—Bulk Flow Measurement

—Shroud
—Nozzle Inlet
—Transition Zone
—Nozzle Exit

—Straight Lines
—Bends
—Expansions
—Contractions
—Splitters
—Mixers

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Figure 1b — Generic sampling system. Component hierarchy of a sampling system.

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expansions, contractions, flow splitters or mixing elements. Splitters are used where it is desired to extract a sample from the duct or stack with a single system and then to provide samples to multiple collectors or monitors. In some situations, flow conditioning apparatus is used to dilute or concentrate a sample, or to selectively remove constituent gases (e.g., water vapor in order to minimize the risk of condensation). When a sampling system is used with a collector such as an aerosol filter, the sample may be analyzed in a laboratory that is remote from the sampling site. If a continuous monitor is used, the purpose of the monitor is to provide a near realtime signal of the concentration of the radionuclides of interest. The flow control system serves the function of providing the flow through the sampling system, of measuring that flow, and of maintaining its value at a desired level.

3.1 Definitions

In this standard the following definitions apply:

3.1.1 AD: See *Aerodynamic diameter*.

3.1.2 absorbent: A material that takes up a constituent through the action of diffusion, allowing the constituent to penetrate into the structure of the absorbent (if a solid) or dissolve in it (if a liquid). When chemical reaction takes place during absorption, the process is called chemisorption.

3.1.3 accident (conditions): Upset conditions that can lead to the release of abnormal concentrations of radionuclides from a stack or duct.

3.1.4 action level: The threshold concentration of an effluent contaminant at which an appropriate action is to be performed.

3.1.5 adsorbent: A material, generally a solid, which retains a substance contacting it through short range molecular forces that bind the adsorbed material at the surface of the material.

3.1.6 aerodynamic diameter (AD): The AD of a particle of arbitrary shape and density is the diameter of a spherical water droplet that has the same sedimentation velocity in quiescent air as the arbitrary particle.

3.1.7 aerosol: A dispersion of solid or liquid particles in air or other gas.

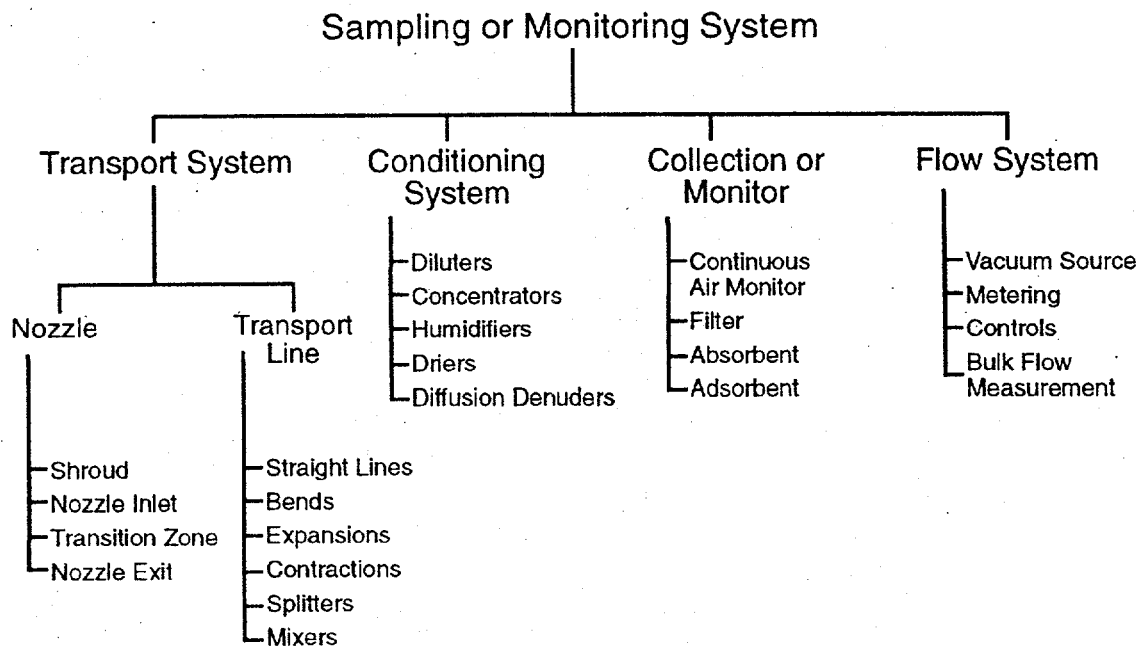**3.1.8 aerosol, monodisperse:** An aerosol comprised of particles that are all of approximately the same size. In general, the geometric standard deviation of a monodisperse aerosol is less than or equal to 1.1.

3.1.9 aerosol, polydisperse: An aerosol comprised of particles with a range of sizes. In general, the geometric standard deviation of a polydisperse aerosol is greater than 1.1.

3.1.10 analyzer: A device that provides for near realtime data on radiological characteristics of the gas (air) flow in a stack or duct. Usually, an analyzer will evaluate the concentration of radio-nuclides in a sampled air stream; however, some analyzers are mounted directly in a stack or duct, or are placed on the outside wall of the stack or duct, and have no flow through them.

3.1.11 ANSI: Abbreviation for the American National Standards Institute, Inc.

3.1.12 ASME: Abbreviation for the American Society of Mechanical Engineers.

1   **3.1.13 aspiration ratio:** Used in conjunction with the performance of a nozzle. It is the ratio of
2   aerosol concentration at a nozzle inlet plane divided by the aerosol concentration in the undisturbed
3   stream at the point where the nozzle is located.
4
5   **3.1.14 bend:** A gradual change in direction of a sample transport line. The radius of curvature of
6   a bend should be at least three times the inside diameter of the tubing.
7
8   **3.1.15 bulk stream:** The air flow in a stack or duct, as opposed to the sample flowrate.
9
10   **3.1.16 burial:** The imbedding of a particle into a filter medium or the masking of a particle by
11   subsequent deposits of particulate matter.
12
13   **3.1.17 calibrate:** Adjustment of a system and the determination of system accuracy using one or
14   more devices that are either traceable to the National Institute of Standards and Technology (NIST)
15   or based on first principles. Includes adjustment of flow, temperature, humidity, or pressure gages
16   and the determination of system accuracy using the NIST-approved or first- principles equipment.
17
18   **3.1.18 CFR:** Abbreviation for the Code of Federal Regulations.
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20   **3.1.19 coefficient of variation (*COV*):** A statistic that is the ratio of the standard deviation of a
21   variable to the mean value of that variable.
22
23   **3.1.20 collector:** A device at the end of a sampling system that is used to retain radionuclides for
24   analysis, e.g., a filter that is used to remove α-emitting transuranic or other radionuclide aerosol
25   particles from a sample stream.
26
27   **3.1.21 concentrator:** A device that is used to increase the concentration of contamination in a
28   sample stream.
29
30   **3.1.22 conditioning system:** Apparatus that could be used to purposefully, in a controlled manner,
31   change the aerosol concentration, gas composition, particle size distribution, temperature or
32   pressure in a sample stream (see figure 1).
33
34   **3.1.23 continuous air monitor (CAM):** A near realtime analyzer that provides data on radionuclides
35   (e.g., concentration of α-emitting aerosol particles) in a sample stream.
36
37   **3.1.24 continuous monitoring:** Either uninterrupted sampling or sequential collection of a sample
38   obtained automatically at intervals short enough to yield results that are representative for the entire
39   sampling period. Sample may be analyzed in near realtime or it may be analyzed post-sample
40   collection in a remote laboratory.
41
42   **3.1.25 control equipment:** Apparatus used to reduce contaminant concentration in the airflow
43   exhausted through a stack or duct.
44
45   **3.1.26 curvature ratio:** The ratio of bend radius to the tube diameter.
46
47   **3.1.27 cutpoint:** Used in conjunction with a device that causes a separation of aerosol particles by
48   size. It is the aerodynamic particle diameter for which the device will collect 50% and will transmit
49   50% of the aerosol particles.
50
51   **3.1.28 depositional losses:** Loss of sample on the internal walls of a sampling system. See also
52   *wall losses.*

3.1.29 detection limit: The minimum input signal to an instrument that can be said, with a predetermined confidence level, to exceed the inherent noise of the instrument.

3.1.30 diffusion denuder: A device that is used to selectively remove molecular constituents from a sample air stream.

3.1.31 diluter: A mixing device that is used to reduce the concentration of radionuclides, background contamination, or water vapor in a sample stream. Usually, a sample stream taken from the stack or duct is mixed with dry filtered air in a diluter.

3.1.32 drier: A device for removing water vapor from a sample stream.

3.1.33 droplet: A liquid aerosol particle.

3.1.34 effluent: A waste stream flowing away from a process, plant, or facility to the environment. In this Standard, the focus is on effluent air that is discharged to the atmosphere through stacks and ducts.

3.1.35 emission: Contamination that is discharged into the environment.

3.1.36 emit: The process of discharging contaminants into the environment.

3.1.37 EPA: Abbreviation for the U.S. Environmental Protection Agency.

3.1.38 extractive sampling: The process of removing a sample of the flow stream in a stack or duct and transporting it out of the stack or duct for collection or analysis.

3.1.39 fibrous filter: A filter consisting of a mat of randomly oriented fibers.

3.1.40 flowrate: The rate at which mass or volume of gas (air) crosses an imaginary cross sectional area in either a sampling system or a stack or duct. The rate at which volume crosses the imaginary area is called the *volumetric flowrate*; and, the rate at which mass crosses the imaginary area is called either the *mass flowrate* or the *volumetric flowrate at standard conditions*.

3.1.41 fraction of allowable limit (FAL): A multiplier to be applied to an applicable state or federal dose limit for the purpose of developing a graded approach to sampling and monitoring. For each potential impact category, there should be a corresponding fraction of an allowable limit that provides a quantifiable basis for decisions regarding the required monitoring or sampling procedure.

3.1.42 geometric mean: If there are N observations made of a statistical random variable, x, the geometric mean of the sample, x_g is defined

$$\ln x_g = 1/N \sum_{i=1}^{N} \ln x_i$$

3.1.43 geometric standard deviation: If there are N observations of a random variable, the geometric standard deviation, s_g, is calculated from:

$$\ln^2 s_g = 1/(N-1) \sum_{i=1}^{N} (\ln x_i - \ln x_g)^2$$

where x_g is the geometric mean of the random variable.

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3.1.44 grab sample: A single sample removed from a flow stream over a relatively short interval of time.

3.1.45 graded approach (to sampling): A decision process in which the requirements on the system vary with the risk of exposure to radionuclides.

3.1.46 HEPA (high efficiency particulate air) filter: A fibrous filter used for collecting aerosol particles from a flow stream. A HEPA filter collects at least 99.97% of aerosol particles of 0.3 μm diameter and is designed to collect greater fractions of aerosol particles with diameters either larger or smaller than approximately 0.3 μm.

3.1.47 humidifier: A device for adding water vapor to a sample stream.

3.1.48 hydraulic diameter: A parameter that is equal to the actual diameter of a circular stack or duct and is equal to (2 H W)/(H + W) of a rectangular stack or duct, where W = width of the duct cross section, and H = height of the duct cross section.

3.1.49 in-line: A system where the detector assembly is adjacent to, or immersed in, the effluent airstream.

3.1.50 impaction: A process by which a particle or droplet is removed from an airstream by striking an object in the airstream. Curvature of air streamlines, principally on the front side of the object, cause particles with sufficient inertia to strike the object while the air flow passes around it.

3.1.51 interception: A process by which a particle is removed from an airstream by an object in the flow, where the trajectory of the particle's center of gravity would miss the object, but the body of the particle strikes the object.

3.1.52 isokinetic: A condition that prevails when the velocity of air at the inlet plane of a nozzle is equal to the velocity of undisturbed air in a stack or duct at the point where the nozzle inlet is located. *Anisokinetic* is the antonym of isokinetic. *Subisokinetic* refers to the condition where the nozzle inlet velocity is less than the free stream velocity. *Super-isokinetic* refers to the condition where the nozzle inlet velocity is greater than the free stream velocity.

3.1.53 joiner: A device that joins two or more sample streams to form a single sample stream. A typical example of a joiner is a Y-fitting where the flow enters the Y-fitting through the two arms of the Y and leaves through the single leg of the Y.

3.1.54 LLD: Abbreviation for the lower limit of detection.

3.1.55 mass size distribution: A representation of the amount of mass of particulate matter associated with intervals of particle size, over the full size range encountered in a sample. For nuclear aerosol samples, it is a representation of the relative amount of mass (measured mass in a size interval divided by the total mass of the sample) associated with intervals of aerodynamic diameter.

3.1.56 may: In regulatory applications implies an action is not mandatory, but is permissible.

3.1.57 membrane filter: Filter media consisting of thin organic-based films having a range of selectable porosities and controlled composition. Thin porous metallic filters are sometimes also called membrane filters.

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3.1.58 micrometer: A unit of length equal to 1.0×10^{-6} meters that is commonly used to describe the size of an aerosol particle. It is abbreviated μm.

3.1.59 mixing element: A device placed in a stack or duct that is used to augment mixing of both contaminant mass and fluid momentum.

3.1.60 monitor: (v) To measure an airborne radioactive constituent or the gross content of radioactive material continuously or at a frequency that permits an evaluation of concentration over an interval of time. (n) The instrumentation or device used in monitoring.

3.1.61 NIST: Abbreviation for the National Institute of Standards and Technology.

3.1.62 nozzle: A device used to extract a sample from an effluent flow and transfer the sample to a transport line or collection device. Within the nozzle there will be a transition zone where the sample stream adjusts to the conditions in the transport line.

3.1.63 nozzle exit (plane): An imaginary plane across the cross section of a transport system that divides the nozzle region from the transport line. Frequently, the nozzle is a separate component and the nozzle exit plane is clearly defined as the downstream end of that component. If there is no separate component, the nozzle exit is the end of the transition zone of the nozzle flow.

3.1.64 nozzle inlet (plane): The imaginary cross sectional inlet plane of a nozzle where the flow first enters the transport system. In the special case of a shrouded nozzle, the inlet is referenced to the inner nozzle rather than the shroud.

3.1.65 number size distribution: A representation of the number of particles associated with intervals of particle size, over the full size range encountered in a sample. For nuclear aerosol samples, it is a representation of the relative number of particles (measured number of particles in a size interval divided by the total number of particles in the sample) associated with intervals of aerodynamic diameter.

3.1.66 off-line: A system whereby a sample is withdrawn from the effluent stream and analyzed at a location that is remote from the region where the sampling system is located.

3.1.67 off-normal (conditions): Conditions that are unplanned with unknown consequences. Examples are accidents and equipment failure.

3.1.68 particle: An aggregate of molecules, forming a solid or liquid, ranging in size from a few molecular diameters to tenths of millimeters (several hundred micrometers).

3.1.69 particle, large: A large particle is one with a size greater than 10 μm AD.

3.1.70 penetration: The degree of passage of airborne contaminant through a transport system or transport line.

3.1.71 potential effective dose equivalent (PEDE): The dose, in mrem, that the most affected member of the public could receive in a year if control equipment were rendered ineffective. The requirements for continuous monitoring of a stack or duct depend upon the PEDE value.

3.1.72 potential emissions: Radionuclides that could be released to the environment from a stack or duct if there were no control equipment.

3.1.73 potential impact category (PIC): A ranking classification of potential radiological impact, such as potential effective dose equivalent (PEDE). It is used to implement a graded approach to sampling and monitoring. The potential for impact is based on facility source characteristics, assuming loss of containment of the effluent stream under consideration.

3.1.74 precision: The degree of agreement of repeated measurements of the same property, expressed in terms of the dispersion of test results about the mean result. A value of precision is obtained by repetitive testing of a homogenous sample under specified conditions. The precision of a method is expressed quantitatively as either the standard deviation computed from the results of a series of controlled determinations or as the coefficient of variation of the measurements.

3.1.75 probe: a term sometimes used colloquially to refer to the equipment inserted into the stack or duct, usually a nozzle and part of the transport line.

3.1.76 propagated uncertainty: The uncertainty of a dependent variable of a measurement system as affected by the combined uncertainty of independent variables.

3.1.77 quality assurance: Planned and systematic actions necessary to provide confidence that a system or component will perform satisfactorily in service and that the results are both correct and traceable.

3.1.78 radionuclide: An unstable isotope of an element that decays or disintegrates spontaneously, emitting radiation.

3.1.79 rake: A probe within a stack or duct to which two or more nozzles are attached.

3.1.80 record sample: A sample that is collected for reporting purposes. Generally, record samples are analyzed off-line.

3.1.81 reference method: Apparatus and instructions for providing results against which other approaches may be compared. Application of a reference method is assumed to define correct results.

3.1.82 representative sample: A sample with the same quality and characteristics for the material of interest as that of its source at the time of sampling.

3.1.83 sample: A portion of an airstream of interest, or one or more separated constituents, from a portion of an airstream.

3.1.84 sample extraction location: The location in a stack or duct that coincides with the nozzle inlet. Generally, it is taken as a plane that is perpendicular to the longitudinal axis of a stack or duct.

3.1.85 sampler: A device that collects or analyzes the sampled air flow from a stack or duct.

3.1.86 sample stream: Air that flows through a sampling system.

3.1.87 sampling environment: The condition of the flow and gas within a stack that can influence the sampling process. Factors include pressure, temperature and molecular composition of the gas.

3.1.88 sampling location: See *sample extraction location*.

3.1.89 sampling system: With reference to the diagram given in figure 1, a general sampling system consists of a probe, a transport line, a flow conditioning system and a collector or monitor. Depending upon the application, a flow conditioner may not be used in the sampling system.

3.1.90 scrubber: A device for allowing air and liquid streams to achieve intimate contact to effect a transfer of gases, liquids, or solids carried in the gas to the liquid stream. The liquid may be a static pool through which the gas rises, or may be sprayed into a flow column or passed through packing.

3.1.91 sedimentation velocity: The terminal (maximum) velocity an aerosol particle attains in quiescent fluid (air) as a result of the gravitational force.

3.1.92 sensitivity: The change in reading of a mechanical, nuclear, optical or electronic instrument as affected by changes in the variable being sensed by the instrument. The slope of a calibration curve of an instrument, where a calibration curve shows output values of an instrument as a function of input values.

3.1.93 shall: In regulatory compliance means an action is mandatory.

3.1.94 should: In regulatory compliance indicates an action is desirable but not mandatory.

3.1.95 shroud: An aerodynamic decelerator placed about a sampling nozzle to improve aerosol particle sampling.

3.1.96 splitter: A device that divides a sample stream into two or more parts. The usual goal in the design of a splitter is to have equal concentrations in each of the exit flows from the splitter.

3.1.97 standard conditions: Used to convert air densities to a common basis. The standard conditions adopted in this Standard are a temperature of 25°C and a pressure of 760 mm Hg.

3.1.98 swirl: A condition when the velocity vectors of a flow are not aligned with the longitudinal axis of the stack or duct.

3.1.99 transition zone. A region in a transport system where the air flow characteristics change. For example, this could be the region where the sampled stream in the nozzle adjusts to the transport line geometry.

3.1.100 transmission ratio: Used in quantifying performance of nozzles. It is the ratio of aerosol concentration at the exit plane of a nozzle to the aerosol concentration in the undisturbed flow in the stack or duct at the point where the nozzle is located.

3.1.101 transport line: That part of a transport system between the nozzle exit plane and the entrance plane of a collector or analyzer.

3.1.103 transport system: Apparatus that samples a stream from a stack or duct and carries it to a collector or analyzer.

3.1.104 uncertainty: An estimate of the relative error in the accuracy of a variable. It is generally taken as the ratio of an estimated standard deviation of a variable (due to random errors) to the mean value of the variable.

1 **3.1.105 uncertainty analysis:** A procedure for estimating the overall impact on the accuracy of a
2 dependent variable as a result of estimated errors in independent variables.
3
4 **3.1.106 vapor:** The gaseous form of materials that are liquid or solids at room temperature, as
5 distinguished from noncondensible gases. (Vapors are gases but carry the connotation of having
6 been released or volatilized from liquids or solids.)
7
8 **3.1.107 velocity profile:** A map of the velocity values at a given cross section in a stack or duct.
9
10 **3.1.108 volatile:** Having a high vapor pressure that will allow significant quantities of material to
11 become gaseous at the prevailing temperature. In this Standard, the stack temperature would
12 generally be considered as the reference.
13
14 **3.1.109 wall losses:** Loss of sample to the internal walls of a transport system. Quantitatively, it
15 is the equivalent concentration lost to the walls of a nozzle, transport line, or transport system
16 divided by the concentration at the inlet plane of the nozzle, transport line, or transport system.
17
18 **3.2 Nomenclature**
19
20 Symbols that are used in equations in this standard are defined in this section.
21
22 A — Cross sectional area of a stack or duct, m^2
23
24 A_e — Aspiration efficiency of a sampling nozzle, dimensionless
25
26 C — Cunningham's slip correction for aerosol particles, dimensionless
27
28 C_{af} — Velocity-averaging correction factor for determining flowrate in a stack or duct from a
29 line average velocity taken with an acoustic flow meter, dimensionless
30
31 C_P — Pressure coefficient for a pitot tube, dimensionless
32
33 C_{pt} — Velocity-averaging correction factor for determining flowrate in a stack or duct from a
34 single point reading with a pitot tube, dimensionless
35
36 C_{ta} — Velocity-averaging correction factor for determining flowrate in a stack or duct from a
37 single point reading with a thermal anemometer, dimensionless
38
39 c_e — Radionuclide concentration at the exit plane of a transport system component, mass
40 or activity/m^3
41
42 c_i — Radionuclide concentration at the inlet plane of a transport system component, mass
43 or activity/m^3
44
45 c_∞ — Radionuclide concentration in the undisturbed free stream at the nozzle location,
46 mass, or activity/m^3
47
48 D_a — Aerodynamic particle diameter, m or μm
49
50 De — Dean number of a flow bend ($De = Re/R_c^{1/2}$), dimensionless
51
52 d_t — Inside diameter of a transport system component (e.g., tube), m

L Length of a section of tubing, m

M Mean molar mass of a gas, kg/kmol

N Number of points or observations

P Overall penetration of sample through a transport system, dimensionless

P_j Penetration of sample through the jth component of a transport system, dimensionless

p Pressure, kPa or mm Hg

p_{std} Standard pressure, 101.3 kPa or 760 mm Hg

Q_T Total volume of gas (air) sampled, m³

q Volumetric flowrate, m³/s or liter/min

q_a Volumetric flowrate at actual temperature and pressure conditions, m³/s or liter/min

q_{std} Volumetric flowrate at standard conditions (25° and 760 mm Hg), m³/s

R Gas constant for a particular gas (R_u/M), kJ/(kg°K)

R_c Radius of curvature of a pipe bend, m

R_o Curvature ratio ($R_o = R_c/d_t$), dimensionless

R_u Universal gas constant, $R_u = 8.314$ kJ/(kmol•K)

Re Reynolds number of flow in a tube ($Re = \rho U_m d/\mu$), dimensionless

r resuspension rate, time^{-1}

S Signal

Stk Stokes number, $Stk = C\rho_w D_a^2 U_m/9\mu$, dimensionless

T Temperature, °C or K

T_a Temperature in stack or duct, °C or K

T_{std} Standard temperature, 25°C or 298 K

T_r Transmission ratio of a nozzle, dimensionless

t Time, s

U_m Spatial mean velocity of gas (air) in a flow tube, m/s

V Velocity, m/s

1	V_i	Velocity at the midpoint of the ith element
2		
3	V_{std}	Equivalent velocity at standard conditions (25°C and 760 mm Hg), m/s
4		
5	v_d	Deposition velocity due to Brownian diffusion or turbulent inertial deposition on the
6		wall of a transport tube, m/s
7		
8	v_e	Effective deposition velocity of contaminant at the wall of a transport tube, m/s
9		
10	v_g	Sedimentation velocity of an aerosol particle, m/s
11		
12	Wl	Wall losses of aerosols in transport system components, dimensionless
13		
14	σ	Angular coordinate in a tube cross section, dimensionless
15		
16	Δ	Difference of two values of a parameter
17		
18	η	Efficiency, dimensionless
19		
20	Θ	Time period over which sampling is performed, s
21		
22	μ	Dynamic viscosity of a gas, Pa•s
23		
24	ρ	Density, kg/m³
25		
26	ρ_{std}	Density of air at standard conditions (25° and 760 mm Hg), 1.184 kg/m³
27		
28	ρ_w	Density of water at 4°C, 1000 kg/m³
29		
30	ϕ	Angle of inclination of a tube axis relative to vertical, dimensionless
31		
32	ϵ	Surface roughness, μm
33		
34	λ	decay constant, time⁻¹
35		
36		

4 Objectives and approaches for sampling programs

A written technical basis shall be prepared for the programs and procedures to monitor the releases of airborne radioactive substances from the ducts and stacks of nuclear facilities. Issues to be addressed shall include the sampling objective, the graded approach for meeting the objectives, the relevant facility operating conditions and airborne contaminants, and the action levels for signifying changing conditions. These issues set the bounds or parameters governing the overall design of sampling system placement, components and operation as detailed in clauses 5, 6 and 7.

4.1 Defining the sampling objective

There are many possible objectives for an air sampling program. The rationale in choosing a specific objective and approach shall be well documented. Some possible air sampling objectives are:

— meeting regulatory requirements;

— assessing the need for a permanent sampling or monitoring program;

— assisting in evaluating claims of radiation injury by workers or others;

— measuring the release of radioactive materials to the environment through source sampling;

— helping to ensure that people in the surrounding environment are not exposed to levels of airborne materials exceeding established limits;

— helping to assess the possible consequences of nonroutine incidents and to help in the selection of appropriate corrective action. This can include the integration of radioactive contamination released to the environment over various time periods.

Design of a technically defensible extractive sampling program (i.e., removing a portion of the effluent from the stream for subsequent detection or analysis) requires a clear understanding of these objectives. Many, but not all, objectives are related to worker or environmental protection and regulatory compliance. Failure to understand the sampling objectives can lead to inappropriate or ineffective system design and implementation. For example, if exploratory sampling data are required to evaluate an uncharacterized or poorly characterized source, it may be appropriate to begin the evaluation using rugged portable equipment. Immediate use of highly sensitive or specialized equipment may lead to costly equipment damage or invalid results. At the same time, if long-term, repetitive sampling and monitoring data are required, efforts should be made to design systems with long-term reliability and ease of operation. The design and implementation of a sampling and monitoring plan for the ducts and stacks in a particular facility involve matters of engineering judgement in which conflicting demands arise from consideration of obtaining the most accurate sample, ensuring worker safety, physical plant constraints, and other operational and safety factors that have to be balanced.

The various objectives for sampling are not (or need not be) mutually exclusive in most stack monitoring circumstances. A sampling system designed to meet one objective may meet other objectives as well. Likewise, there can be a number of approaches taken to achieve a given objective.

4.2 Developing a graded approach to sampling

The nature of an operation or process which creates the potential for airborne radioactive material influences the sampling program design and specific response to regulatory requirements. An operation or process being instituted for the first time may require more frequent and extensive sampling than one that is well understood. In addition, a program that requires more comprehensive monitoring is needed for a facility with an inventory of radioactive materials constituting a significant hazard than for a facility handling a less hazardous inventory.

4.2.1 Estimating potential emissions

A survey shall be conducted of the potential sources of radionuclide emissions at a facility to determine 1) the form and radiological inventory of materials being handled, 2) the potential extent of airborne dispersal of this inventory and resultant concentrations at the facility boundary in the event of accidental loss of filtration and control of stack emissions, 3) the potential effective dose equivalent that would be received by a member of the public if such a release occurs, and 4) a comparison of potential doses to appropriate regulatory limits.

Facility operators shall consider in their estimates of potential emissions and resultant public exposures, that under adverse conditions the facility effluent controls (e.g., filtration and gas holdup) may be completely eliminated. It would, therefore, be inappropriate to use actual measured or reported emissions from a stack as the basis for planning a sampling and monitoring program.

To estimate the potential emissions, it shall be assumed that all emission controls are ineffective. Therefore, the limiting factors determining the source term are the inventory and the physical form of the radionuclides being handled. A simple estimation method is the multiplication of the maximum expected radioactive material inventory by a factor that depends on the physical state of the material. The resultant source term can be input to a meteorological dispersion and dose estimation code for purposes of generating annual potential dose effective equivalent rates to a maximally exposed individual at the facility boundary. Table 1 provides a guide to aid the estimation process.

Other approaches to estimating potential emissions might involve correlating actual measurements of aerosol releases to material inventories for the processes of concern. In circumstances where the source term consists of a mixture of radionuclides, the radionuclides that contribute 10% or more to the total potential, or actual, effective dose equivalent from that source should be identified (or as otherwise required by regulation). Facility owners and operators should be aware that this procedure may be subject to state or federal regulation, and if so, that such regulation shall supersede the proposed strategy.

4.2.2 A graded approach to sampling

A graded approach to establishing a sampling and monitoring program should be undertaken. For example, a sampling program design could be based on the potential that the effluent from a given facility has for contributing to offsite dose. This depends on whether or not the radioactive source materials being handled are easily dispersed (in gaseous form or finely divided powders), and also on their inherent radiological hazard. A facility stack that has the potential for discharging airborne radionuclides in quantities that could cause radiological doses to a member of the public in excess of a small percentage of Federal dose limits would be a candidate for continuous sampling and trending and possibly also continuous monitoring with a sampler fitted with a realtime detector. The decision to utilize realtime monitoring in addition to continuous record sampling would be appropriate for stacks that present the potential for radiological doses well in excess of state or federal dose limits, and would also be appropriate where rapid detection of high levels of contamination during accidental releases is needed. Stacks that have the potential for release of radionuclides to the air in quantities that would contribute less than a small percentage of the regulatory dose limits would typically require only periodic confirmatory measurements.

In the absence of a potential radiological source that could contaminate the effluent, no radioactive air emission sampling would be expected to be required, as in nonradiological stacks at nuclear facilities. However, the absence of a potential source would be subject to periodic review to verify that facility uses have not changed. A possible situation that should be guarded against is one in which a facility is no longer used for handling, storing, or processing radioactive materials, but has

Table 1 — Generalized strategy for estimating emissions for purposes
of designing an appropriate sampling and monitoring program

Physical form or state of radioactive inventory available to release	Multiplicative factor to be used in estimating atmospheric emissions
Gases, condensible and noncondensible, and solids or liquids heated to a high enough temperature to be in a volatilized state	1.0
Liquids or particulate solids	0.001
Solids (other than above states)	1.0×10^{-6}

radiologically contaminated ductwork from previous work. Then continuing monitoring requirements may well apply.

Thus a graded, four-tier program may be developed in which increasingly more sampling and monitoring resources are directed at stacks that have the greatest potential for causing public doses in excess of regulatory limits. Specific state or federal regulations appropriate to the type of nuclear facility stacks identified should be consulted to determine the appropriate basis for determining the potential for release and for dose limit thresholds for each tier. An example of a structure for a graded approach to determining required monitoring of emission points is shown in table 1. This approach employs potential impact categories (PIC) (e.g., potential effective dose equivalent, the dose to the member of the public nearest a facility from an emission) that represent dose consequences that may occur assuming effluent attenuation or filtration devices present in the effluent stream have no effect.

There is no one graded approach that would be appropriate for all facilities. The fractions of allowable dose limits proposed in table 2 are illustrative, and therefore shall be considered superseded by appropriate regulatory requirements. They exemplify how a dose limit standard can be associated with a graded approach to monitoring and sampling planning. As indicated, practical considerations involving such additional factors as worker safety and facility constraints should enter into the decision.

4.3 Considerations for sampling different forms of contaminants

Particular attention should be given to the potential interactions between the operating conditions of the facility, the airborne contaminants, the ventilation components and the sampling system. General considerations for assessing the interactions of facility operating conditions and the characteristics of the airborne contaminants are discussed in the following subclauses. Clause 5 presents details on the selection of sampling locations and clause 6 presents the details on design of the sampling system itself. The ventilation and sampling system components are discussed in clauses 5 and 6. The physical and chemical form of the radioactive and other airborne substances shall be factored into the design of the overall design of the air monitoring program.

4.3.1 Considerations for sampling normal and off-normal conditions

Normal operating conditions are the expected conditions with an expected variability. These are usually the average operating conditions and their variance as defined by statistical terms. The normal operating conditions may have a large range of temperature and flowrates depending on the processes in operation. The effluent monitoring system shall be designed to accommodate these

Table 2 — Graded approach to sampling and monitoring

Potential impact category	Required monitoring and sample analysis procedures	Potential fraction of allowable limit[a]
1	Continuous extractive sampling for a record of emissions and in-line, realtime monitoring with alarm capability; consideration of separate accident monitoring system	> 0.1
2	Continuous extractive sampling for record of emissions, with retrospective, off-line periodic analysis	>0.01 and ≤ 0.1
3	Periodic confirmatory extractive sampling and off-line analysis	>0.0001 and ≤0.01
4	Annual administrative review of facility uses to confirm absence of radioactive materials in forms and quantities not conforming to prescribed specifications and limits	≤0.0001

[a] These are suggested limits and will be used as suggested limits throughout the standard. Nevertheless local regulations shall be used.

conditions. The effluent discharge system may also operate with an effluent control (clean-up) system in place that reduces particulate and gaseous emissions to an acceptable level. Therefore, normal conditions exist for particle size and concentration and effluent reactivity and corrosivity. The effluent monitoring system shall be designed to withstand, sample, and record under these normal operating conditions.

Other expected operating conditions may exceed the design conditions for short durations. These conditions may occur during process changes or regular maintenance. Such changes of conditions should be considered design conditions if potential emissions during these periods are likely to exceed 10% of the total expected emissions. They should be considered off-normal conditions if they occur for only brief periods on an infrequent basis, such as once every 6 months, and are unlikely to involve more than 10% of the total expected emissions.

Off-normal conditions are generally considered to be unplanned with unknown consequences. They may result from:

— Accidents such as fires, explosions, spills, or natural disasters;

— Incidents, which are planned events whose outcomes were not fully anticipated or in which an accident or error altered the outcome; or

— Equipment failures, which are events that alter the quality of the effluent, particularly such failures of the effluent clean-up system as leaking or damaged filters or loss of fluid to spray systems or traps.

Off-normal conditions may include the following:

— off-normal flow conditions (low or high flowrate in stack or duct, laminar rather than turbulent mixing conditions);

— off-normal temperature conditions (high or low);

— off-normal gaseous constituents (corrosive, humid, condensing, vaporizing, high concentration, unknown composition);

— off-normal particle characteristics (high concentration, unusual particle shape, exceptionally large size).

Any one or a combination of these conditions may be possible and may alter the collection characteristics of the sampler. If any of these conditions are possible and probable, then the sample should accommodate the conditions or account for the effect and the resulting nonrepresentative sample. If necessary, a back-up system should be provided that can increase the range of sampling conditions.

An effluent monitoring system should be able to accommodate or account for off-normal conditions. However, there are limits to the ability to accommodate and account for off-normal conditions, which may be expected to be reached well before the existence of the facility is threatened. Nevertheless, conditions of a low probability may occur that are markedly different from the expected conditions. These conditions may constitute a recognizable emergency or may result from an incident in which the consequences are recognized only after the fact. The effluent monitoring system could be the only, or the most immediate, means for recognizing the incident or accident.

A sampling system that is capable of accommodating all off-normal conditions, due to its inherent design or because it is sufficiently controlled to alter its sampling characteristics to fit the altered sampling conditions, meets all requirements for off-normal conditions. A sampling system that requires a back-up system or a calculational algorithm to account for the off-normal conditions should monitor the off-normal conditions sufficiently to institute the back-up or to provide the necessary information for calculation. In any case, off-normal conditions may require alerting necessary personnel and instituting corrective actions in addition to obtaining a representative sample.

4.3.2 Sampling for aerosol particles

A representative sample of aerosol particles should not alter the radiochemical and physical characteristics so that analytical interpretation could be compromised. Special attention should be given to the design of the sampling nozzle and transport line so that excessive sample loss and discrimination between particles of various sizes are minimized. Detailed guidance for particulate extraction and transport line design is provided in clause 6.

Studies may be necessary to establish the size distribution and chemical nature of airborne particles in an effluent as an aid to the sample system design. Changes in the nature of effluent components should be anticipated with changes in operations. The possibility that appropriate sampling equipment modifications may be required should be kept in mind.

The sampling and monitoring system should be designed so that emissions occurring under accidental or off-normal conditions can be adequately sampled and detected. This is especially important if the effluent is filtered prior to discharge. Although the particle size most likely to

1 directly penetrate HEPA (high efficiency particulate air) filter media is approximately 0.3 μm
2 diameter, it is erroneous to assume that the sampling system need only be designed for sub-
3 micrometer particles. Larger size particles are transmitted through HEPA filter banks due to small
4 openings in HEPA frames, gasket seals, and filter media defects developing after periods of use.
5 The major factor determining downstream particle size distribution is the distribution of the
6 challenge aerosol. When accidental or off-normal conditions are considered, a wide range of
7 particle sizes may be present in the effluent, and this shall be a factor in the design. Particles well
8 into the inertial size range should be considered to be present.
9
10 The off-normal case should consider the consequences of enhanced leakage of particles through
11 filter media, filter seals, and cracks in filter frames. Thus, both normal and off-normal conditions are
12 characterized by chronic, low-level releases involving particles in size ranges covering nearly the full
13 spectrum of sizes present in the challenge aerosol. The accident case involves failures of potentially
14 much greater consequence, with high radionuclide concentrations in the effluent. In either case, a
15 polydisperse aerosol (an aerosol with a range of particle sizes) shall be anticipated. But the accident
16 case is much harder to characterize in advance because changes in effluent discharge rate, added
17 dust, smoke, and debris may be expected. However, it should be noted that particles greater than
18 about 100 μm would not be expected to occur in large numbers in a stack effluent due to gravita-
19 tional settling and inertial impaction removal effects during transport in the accident environment,
20 and in the ductwork leading to the stack. The transport of such large particles in extractive sam-
21 pling lines is exceedingly inefficient or nonexistent. Therefore, there are upper bounds to particle
22 sizes which need to be evaluated. For typical stack conditions, evaluation with 10 μm AD particles
23 should suffice; for the accident case, consideration of transport of somewhat larger particles is
24 prudent. Annex G should be consulted for a discussion of the particle sizes associated with a
25 variety of source terms and sampling concerns. The facility designer or evaluator should use
26 modeling tools like those discussed in clause 6 to understand the expected performance of any
27 proposed sampling system under a variety of conditions.
28
29 A record sample is collected to minimize sample loss or bias created by complex sample transport
30 line design or by realtime detector chamber design. Consideration should be given to the feasibility
31 of collecting such a sample by means of an in-line sampler mounted directly in the stack flow rather
32 than using an extractive system.
33
34 A continuous air monitor (CAM) sample is obtained to enable near realtime detection of radionu-
35 clides in the effluent. It is usually desirable to obtain a sample containing as much of the largest
36 size particles as feasible because of the increased activity associated with those large particles.
37 However, if there are usually large quantities of inert large particles present along with radioactive
38 particles, there may be an offsetting disadvantage to optimizing collection of large particles due to
39 sample burial and radiation attenuation effects. Then, consideration of size-selective sampling
40 techniques that discriminate against larger inert particles is warranted.
41
42 The system design chosen to supply aerosol samples to either a continuous air monitor or an in-line
43 record sample filter (or both) shall be designed and evaluated to meet minimum performance
44 objectives under normal, off-normal, and accident conditions with respect to the efficiency of
45 particle transport to the filter, bias with respect to size or kind of particle, and allowable total
46 random error. As discussed in the balance of this standard, performance objectives for these
47 conditions will include many factors in addition to the central concern for providing an
48 representative sample of the effluent.
49

20

4.3.2.1 Concerns for large particles

The guidance presented in this document is primarily directed to sampling particles that pose inhalation risks. Thus, the particle sizes of major concern are generally less than or equal to 10 μm aerodynamic diameter (AD). If, however, there is a process or source feeding a monitored effluent that can release aerosol particles much larger than these sizes into the effluent stream, a special sampling apparatus located in the duct near the process should be designed that would reliably detect failure of emission controls on that source. The performance of such apparatus should be verified for the range of anticipated particle sizes and sampling conditions (e.g., stream velocity, mixing, etc.) at that location. As previously noted, use of HEPA filtration upstream of the sample withdrawal location does not eliminate all concerns for large particles due to transmission through leaks in frames and seals. However, even nonfilterable radioactive gases and vapors may become associated with large particles by adsorption effects. For example, radioactive vapors or gases penetrating filtration can deposit on downstream stack or duct walls and become incorporated into surface layers, corrosion, or rust. Subsequent flaking or shedding of these layers may lead to the release of large radioactive particles that may go undetected by sampling systems that are optimized for collection of small particles. Alternate approaches to extra-large particle sampling may involve the periodic use of impaction plates or other specialized in-stack samplers or detectors to provide effective and timely samples and detection.

4.3.3 Sampling condensible vapors or reactive gases

The presence of radioactive air contaminants in the form of condensible vapors or reactive gases, such as certain forms of radioiodine, in the effluent stream will create a potential for serious distortions in the sample if precautions are not taken in the design and operation of the sampling system. Deposition in long transport lines and condensation due to temperature changes in the line should be avoided. The inner surfaces of the sampling probe and transport line should be constructed of or coated with nonreactive materials to minimize surface interactions with the sample. The possibility for conversion of a portion of the sample by chemical transformations induced by the sample transport process, such as conversion of tritium gas into tritiated water, should be understood and accounted for in the sampling system design. Conditioning the sample itself may be necessary, such as deliberately changing the temperature or purposefully diluting the sample with a carrier gas. The presence of nonradioactive constituents which could undergo phase changes that could cause loss or distortion of the sample, such as the condensation of water vapor, should also be taken into account in sample system design. Further discussion of special considerations related to sampling vapors and condensible gases is found in clause 6.

4.3.4 Sampling noncondensible, nonreactive gases

If the radioactive contaminant in the effluent stream is a noncondensible, nonreactive gas (e.g., krypton-85), then it is not as critical to avoid long transport lines as it is for the other types of contaminants described above. Chemical or phase change interactions may not be a factor for system design.

4.4 Determining monitoring action levels

The action levels required of the air sampling system and program shall be considered as part of the design basis. The desired action levels determine the sensitivity requirements of the sampling system and affects design parameters such as sample volume, sampling frequency, the capacity of the collector, and the sensitivity of on- or off-line analyzers.

An action level is an effluent contaminant concentration threshold at which an appropriate action should be performed. The type of action performed depends on the circumstances. The action may entail generation of alarms, diversion of effluent through added effluent treatment, or intervention in the process creating the contaminant. There are inevitable consequences of whatever response is taken. Some are relatively minor, others are much more significant in terms of cost, damage to equipment, and possibly even human health and safety. Careful consideration shall be given to the setting of an action level for an effluent monitoring system that takes into account all such consequences. Not only can there be false negative outcomes (i.e., a true release of significance goes uninvestigated), but also false positive outcomes (i.e., worker responses to alarms, risks associated with rapid shutdown, and costs are incurred needlessly). Both types should be anticipated, but, depending on the hazard potential of a particular stack effluent and other factors, false positive outcomes may be of more consequence to facility operations and worker safety than false negative ones due to work stoppage and evacuation of areas. Facility administrators should be cognizant of all reasonably anticipated outcomes.

The process of selection of an appropriate action level requires an understanding of 1) the physical and chemical characteristics of the contaminant, 2) the characteristics of the sampling system required to obtain a sample of the contaminant for analysis and counting (e.g., the nozzle design characteristics, the transport line design, or sampling location), and 3) the type, intensity, and variability of interference with the measurement. Each of these three factors can contribute uncertainty to the contaminant concentration estimate, and, therefore, affect the level of confidence that can be assigned to the decision. The selection of an appropriate action level, given the uncertainties, is separate from and precedes considerations of the required sensitivity of the sampling and measurement systems.

It is useful in the context of discussing action levels to draw distinctions among the following:

— *Control monitoring:* Monitoring for purposes of providing adequate warning so that an operator can take action to protect workers and the public from excessive exposure (i.e., continuous monitoring with alarm in Potential Impact Category 1 stacks of table 2);

— *Monitoring system availability:* Monitoring sampling system availability and response so the facility operators are alerted if equipment failure takes a system off-line or seriously degrades performance;

— *Performance monitoring:* Regulatory compliance monitoring that will yield data of such quality and type that the facility owner can identify and quantify the most significant radionuclides present in the effluent, and support demonstration of regulatory compliance by meeting all requirements for sample extraction location, instrument calibration and maintenance, sample handling and chain of custody (this pertains to Potential Impact Categories 1, 2, and 3, table 2).

When determining action levels, consideration should be given to both accuracy and precision. These terms apply to both the process of sampling and the process of measurement. *Accuracy* is a measure of the degree of deviation between the mean of a set of measurements and the true value. The concern for accuracy is directed at the elimination of bias in the sampling and measurement

processes. Regular calibration of sampling and measuring equipment using accepted procedures and traceable standards is used to establish accuracy. Sampling accuracy can be determined from replicate sampling and comparison using standard methods and devices. Measurement accuracy can be evaluated utilizing measurement statistics and the outcomes of appropriate tests with standards, blanks, and known spiked samples. Sampling and measurement uncertainties are statistically combined to obtain overall bounds on accuracy. Accuracy should be estimated at the 95% confidence level.

Precision, in contrast, is a measure of the reproducibility of results obtained by repeated analysis under the same conditions. Statistical measures of dispersion of results about a measurement population mean is used to calculate precision. Sampling precision can be determined by replicate samples obtained under the same conditions. Measurement precision is obtained from the statistics of repeated measurements on replicate samples and by detailed analysis and propagation of errors in component measurements. Sampling and measuring precision are combined statistically to obtain an estimate of overall precision. The precision shall be estimated at the 95% confidence level. The concern of precision determinations is the estimation, and where possible, reduction of random errors in the sampling and measuring processes.

The departures of measured values from either the true values (accuracy effects) or from the mean of measured values (precision effects) are measures of error or uncertainty in the sampling and measurement system results. Contributions to uncertainty in sampling or measurement are best determined independently and combined by statistical propagation of error. A detailed discussion of sampling and measurement random errors, and error determination methods leading to an assessment of overall effluent monitoring system error, is found in annex E.

A guide to recommended levels of uncertainty, as they pertain to accuracy and precision of sample extraction and transport, and of measurement, are summarized in table 3. Most of the recommendations for control monitoring in table 3 are not as stringent as the recommendations for record monitoring. Near realtime radiation detection by a CAM, for example, usually cannot yield as accurate a measurement as would be expected of a laboratory counting system because variable bias introduced by the presence of interfering background activity can be significantly reduced or eliminated in the laboratory. Note that the accuracy and precision recommendations of table 3 are not meant to be absolutes and be equally appropriate in all cases and conditions. Effluents containing highly reactive constituents such as radioiodine may be particularly difficult to extract and transport without significant sampling bias, for example, leading to higher estimated sampling accuracy uncertainties than 20%. In contrast, measurement accuracy in some systems may be easily held well below 20% given the characteristics of the instrumentation and measurement processes and should be so reported. Each facility should set data quality objectives for its particular sampling and measurement systems.

There are justifiable reasons for sacrificing some degree of control measurement accuracy in order to achieve higher instrument reliability, extended range of response, more effective background compensation, or other optimization goals. The overall system accuracy and precision uncertainty limit values are derived by summing the respective relative variance estimates of the sampling accuracy or precision components. For example, the recommended limit of overall uncertainty in system accuracy for continuous monitors (40%) is the square-root of the sum of squares of the sampling accuracy component (20%) and the measurement accuracy component (35%) of uncertainty. Mentioning these components separately calls attention to the fact that if the sampling nozzle and transport line are not properly designed and properly placed, it will create uncertainty in sampling accuracy, and no amount of attention to measurement accuracy in the system will prevent the system from generating poor, biased data, and faulty alarm responses.

Table 3 — Guide to accuracy and precision of sampling and measurement

Factor or consideration	Record monitoring	Control monitoring
Frequency of		
a) Sampling	Continuous	Continuous
b) Measurement	Weekly	Near realtime
Relative Uncertainty of Monitoring System		
a) Overall Accuracy	±30%	±40%
Precision	±30%	±40%
b) Sampling Accuracy	±20%	±20%
Precision	±20%	±20%
c) Measurement Accuracy	±20%	±35%
Precision	±20%	±35%
System Availability	>90%	> 95%

4.4.1 Action levels for control monitoring

The foregoing discussion provides a basis for incorporating accuracy and precision considerations in the setting of appropriate action levels. There are no hard and fast rules concerning how these levels should be set. It should be kept in mind that there is a trade-off between having high confidence in an alarm being triggered only by a 'true' contaminant release, and having sufficient alarm sensitivity to the presence of the contaminant, albeit at lower confidence. It is in this context that the true costs of false alarms have to weigh into the decision, along with the desire to detect the contaminant at the lowest concentration and shortest integrating time. In some CAM instruments it may be that the net counts are converted to activity concentration estimates by dividing the counts by detector efficiency, volume sampled, and time. All of these factors add uncertainty to the results. However, for alarming purposes, the largest uncertainty will typically derive from the counting error, as shown in annex E. If the costs of false alarms in an effluent monitoring system are large, then a decision may be made to set the alarm threshold at a relatively high level, and accept the risk of not detecting a lower level release in a timely fashion. Trending of measurement results can be a useful tool in some contexts to aid in control below a chosen action level. The user should determine an action level that can be attained, and design and operate the system so the detection limit for that sampling and measurement process is sufficiently below the action level, avoiding false alarms.

Control monitoring (using a CAM with alarm) does not imply that there can be a more relaxed attitude toward achieving a representative sample. In the case of continuous monitoring for particulate radioactivity in effluent streams, there may not always be 'sufficient' small particles in a release to cause an alarm. Nor should it be assumed that in a poorly designed sampling system a few large particles will get through for alarming purposes. Such assumptions are ill-advised and unacceptable. The danger in lack of attention to CAM sampling system design and placement is that the component of the sample that is not well represented (possibly the larger size particles, for example) may be the very component that will provide the best chance for early warning, and hence control, worker protection, and impact limitation. The inherent limitations of providing radiation detection in the sampler during the sample collection process is due to the large background component in the detected signal. Therefore, it is to be expected that the CAM measurement process will be subject to greater uncertainty than would be the case when sampling is followed by

off-line laboratory analysis. The choice of a relatively insensitive sampling system may lead to alarm thresholds consistent with an acceptable false alarm rate. However, the system may then be susceptible to excessive false negative responses that may be of concern to other stakeholders.

4.4.2 Action levels for record monitoring

If elevated concentrations of radioactive contaminants could be present in the effluent stream of high hazard stacks (PIC Category 1 of table 1), there shall be control monitoring. However, any stack that has the potential for radioactive emissions (PIC Categories 1 - 3) should have record monitoring at an appropriate frequency. Record samples are collected continuously in an integrated sample, and then are analyzed by counting retrospectively (off-line). The levels of activity that can be detected by these means are typically many orders of magnitude smaller than those detectable by on-line monitors. Additional sensitivity can be achieved by compositing several week-long samples into monthly or even quarterly samples. The decision to attempt to achieve a certain detection limit goal will have to balance costs, time, and other factors. Uncertainty in the final estimate of quantities, concentration, and rates of emission will have to be propagated from errors in each of the factors entering into the respective calculation.

Once the central estimates and their uncertainties are determined and logged over time, another layer of analysis can be applied. Here the question is not whether a particular measurement is above the decision level for that contaminant, but whether a given trending in the data is normal or indicative of an off-normal condition, or whether a given datum is an outlier or is actually an elevated concentration. For this purpose certain statistical tests and trending procedures (e.g., control chart) are important. A retrospective action level may be set above the trend line in the data (say, at the 3σ level) to help decide whether a datum should be regarded as belonging to the family of normal values for the parameter being measured (e.g., the mean concentration of radioactivity emitted during the previous month or Quarter), or belongs to a new, unidentified situation that requires investigation and intervention. The investigation could determine whether a bias had been introduced in the analytic procedure for radionuclide determination, or in the direction of ascertaining if there exists a small leak in the filtration system of the facility stacks being monitored. The decision on the appropriateness of a given multiplier defining the action level will hinge on the estimated costs associated with either being wrong in concluding that an excursion beyond the action level has occurred, and that controls in a facility are breaking down (false positive), or being wrong about thinking that emission controls and analytic procedures are normal, only to discover later that chronic low-level releases have been undetected (false negative). If the achieved detection limit for a monitoring system is well below the action level, there should be sufficient latitude to eliminate false negatives by trending.

4.4.3 System sensitivity needed to achieve selected action levels

Once an action level has been determined, another issue that must be addressed is whether the proposed monitoring system is sufficiently sensitive (at the 95% confidence level) to meet the need. This is not a question of accuracy, but of whether a chosen system will be able to provide the needed net response above background. Assume that a particular effluent monitoring system or instrument has been operating in a given stack effluent long enough to establish the population of blank responses (meaning zero concentration of radioactive material of concern present, but varying levels of background activity is still present), large enough to reliably establish an estimate of the population mean of the blank, μ_B, and standard deviation, σ_B. While in operation, if there is no contaminant present, but there is an interfering background, the number of net counts S (gross counts - background counts) expected would have a limiting mean of zero, and a standard deviation of $\sigma_S = (\sqrt{2})\sigma_B$ (i.e., the variance in the gross and background counts are essentially the same). If the distribution of counts is approximately normal, then the upper 95% confidence level for the

distribution of the net counts observed in the instrument will be $L_c(0.05) = 1.645\sigma_S = 2.33\sigma_B$. Such a level is often referred to as the decision level or the critical level of the measurement, because when the number of counts exceeds that level, there is only a 5% chance of making the error of concluding that activity is present when there is truly only a background level present (a false positive). Note that the decision level is not the same as the detection limit or MDA level of the system. The decision level is an *a priori* number describing, in effect, the characteristics of the instrument and its operating conditions (levels of interference, counting time, etc), and not a measure of the uncertainty in a particular determination. If the decision level for a given proposed monitoring system is above the desired, or regulatory required level, a more sensitive system shall be developed.

Another type of error that can occur is that of falsely concluding that no activity is present when in fact there is significant radioactivity in the sample. One can define another limit, sometimes called the detection limit or lower limit of detection (LLD), as the mean number of net counts for which the observed net counts are 95% certain to exceed the decision level of the instrument. This avoids errors of the first kind (false positives) and also limits false negative errors. It can be shown that for a well-defined instrument background, and sufficiently large numbers of counts from the sample, the 95% detection limit, or LLD is

$$LLD = 2 L_c(0.05) = 4.65\ \sigma_B \tag{1}$$

The detection limit so defined is clearly also an *a priori* limit. The suitability of a proposed monitoring system to achieve a chosen alarm limit can be evaluated using the LLD concept. An alarm threshold set at the LLD, or $4.65\ \sigma_B$, or possibly larger will provide good immunity from false alarms (errors of the first kind). But it should be determined that it is not essential that sample counts near the critical level trigger an alarm (usually the case).

For example, assume that the standard deviation in a series of integrated count rates from a CAM is $\sigma_B = 1$ unit in relative terms with nominal background interference (typically radon daughter activity) present, but zero concentration of transuranic elements. Then if the alarm threshold set point is chosen to be 4 units $(4\sigma_B)$, the probability of a false alarm when the target radionuclide concentration is zero, is 3.2×10^{-6}. If the set point is increased to 6 units, the probability of false alarm in the presence of zero concentration drops to 9.9×10^{-10}. However, as the multiplier is increased, there is increased probability that low level concentrations of contaminants will not trigger an alarm. Repeated counts as activity continues to accumulate on the sample filter should eventually result in an alarm or become apparent in data trending.

4.4.4 System performance and availability alarms

System performance and availability alarms are a separate consideration from action levels based on effluent releases. The sampling system designer shall consider the need for alarms activated by system component failure which results in the inability to properly sample. Such system failure alarms should be differentiated from alarms triggered by effluent release action levels because a very different response is needed. Establishing system failure alarms should be based on a statistical evaluation and consequence analysis considering acceptable levels of false positives and false negatives as discussed in clause 4.4.3.

System failure can take two forms. The first is a complete failure. Complete failure may be a system shutdown caused by an interruption of power or by the loss of a vital component. The complete failure should be indicated by an alarm to ensure that action is taken to restore operation. A complete failure that is due to the loss of a vital component may need a separate alarm for each

mode of failure because the responses may be different. The importance of the alarm and the priority of response should be determined and entered into the facility alarm and response plan.

The second form is a partial failure that compromises the quality of the output, renders the output unusable, and causes the system to be inadequate for safety or regulatory requirements. This type of failure should require a system alarm and a graded response because there may be differences in operation that require instrument interpretation before activating an alarm. Two examples of partial failure are a significantly reduced sample flowrate or a significant leak in the sample transport system. There are many other possibilities for partial failure and it may be impractical to trigger alarms for them all. Consequently, there are requirements given for maintenance and inspections in clauses 6 and 7.

5 Sampling locations

5.1 Characterizing the sampling environment

The sampling environment within a stack or duct shall be characterized to design the sampling system for those conditions. A number of important parameters should be considered in the design process; however, accident or off-normal conditions shall always be kept in mind. Information used as a basis for design and location of sampling systems shall be fully and carefully documented.

5.1.1 Temperature

The expected temperature range at potential sampling points under normal operating conditions and credible accident conditions should be determined. Often the effluent temperature is very stable. There may be little seasonal variation in temperature as a result of controls in the facility heating, ventilation, and air conditioning operations. Off-normal conditions in many cases may have little effect on temperature; however, any temperature changes could be important to the collection of a sample under off-normal conditions.

5.1.2 Effluent flowrate

Knowledge of effluent flowrate is important in any final calculation of a release rate or a total release. The range of effluent gas velocities are also important in the design and control of the sampling system. The flowrate may change with a diurnal pattern as processes are increased or decreased, as fans are switched on or off for maintenance, as doors are opened or closed, or as heating and cooling systems are actuated. Off-normal conditions may include changing the effluent flow as a means of controlling or mitigating unusual process conditions. Facility design basis accident descriptions, and accident control and mitigation plans, may provide a basis for estimating changes in flow (including substantially reduced flow) as a result of accident conditions. These should be taken into account in the design of a sampling system for a particular facility. For example, the diversion of flow from one stack through an adjacent stack may be a control option that would be exercised if loss of HEPA filtration were to occur in the first stack.

5.1.3 Duct geometry

Duct geometry, including shape (circular or rectangular), main stack flow inlet conditions (e.g., side entry and angled entry at the base), additional lateral entry of contaminated flows, orientation of stack elements with respect to the vertical, and the presence or absence of such flow disturbance elements as bends can all be important factors in the design of proper sampling systems and their locations in the stack. The stack and duct geometry information shall be fully documented.

1   Particular attention shall be given to the geometry of main flow entry conditions because in many
2   cases the presence of angled inputs from fans or transition elements from rectangular to circular
3   geometry can introduce nonaxial velocity components in the flow that can result in swirl and
4   irregularities in aerosol concentration profiles. Any discharge of secondary flows of contaminants
5   into a main stack in a manner that injects contaminants into the boundary layer of the stack shall be
6   recognized and avoided because this can result in contaminant releases that would not be well
7   mixed with the bulk of the flow and, therefore, possibly not be detected.

8
9   **5.1.4 Effluent composition**
10
11   The composition of a stack effluent under both normal and accident conditions shall be taken into
12   account when the design of a sampling system for that stack is developed. Radioactive
13   contaminant characteristics that shall be considered were discussed in clause 4.3. Nonradioactive
14   constituents shall also be identified whenever they may influence the sampling system design. An
15   important example is the presence of strong acid or caustic fumes that could cause rapid
16   deterioration of a nozzle or sample transport line unless suitable compensation is provided by the
17   selection of appropriate materials for construction of nozzles and lines. Inert dust loading in an
18   effluent can also be a factor in the design of appropriate nozzles due to its potential for plugging
19   inlets or interfering in the proper operation of sampling system elements. Moisture content of the
20   effluent can also be a significant factor in the design of sampling systems due to possible
21   interactions with contaminant components, condensation, and plugging of filters.

22
23   **5.1.5 Particle size**
24
25   The efficiency of extracting, transporting, and collecting sampled particles is sensitive to the size
26   (AD) of the contaminant-bearing particles. Consequently, a knowledge of the contaminant particle
27   size distribution under normal, off-normal, and accident conditions is important to the design of the
28   entire sampling system and to the setting of reasonable performance expectations. Mass or activity
29   size distributions shall be used rather than the number size distribution. Size information can often
30   be estimated for normal and off-normal conditions; however, estimates for accident conditions are
31   more tenuous. Rodgers (1995) suggests that for most applications, a particle size of 10 μm AD is
32   appropriate to use in design and evaluation of sampling systems, for both normal and off-normal
33   conditions. Accordingly, the system design should be based on an assumed particle size of 10 μm
34   AD unless there is evidence that a substantial fraction of the aerosol mass or activity will be
35   associated with larger sizes. In the latter case the design should proceed on the basis of an
36   assumed largest AD particle size. For further discussion on particle size as applied to system
37   design, see annex G.

38
39   **5.2 Selection of sampling sites**
40
41   **5.2.1 General considerations**
42
43   Locating a site in a stack or duct where a representative sample can be obtained by extractive
44   methods involves such considerations as the characteristics of the radioactive contaminant, factors
45   associated with equipment placement and support, and worker health and safety. Generally, the
46   sample extraction location should be placed between the discharge plane of a fan and the stack exit
47   plane, with caution that the location should not be so close to the stack exit plane that wind effects
48   can significantly influence the velocity profile at the sampling location. In addition, the sampling
49   location should be in a region where the contaminant profile is well mixed and stable, it should be
50   readily and safely accessible, it should not present a problem for sampling services and maintenance
51   activities, and it should be able to accommodate analysis or collection equipment that does not
52   compromise the quality of the sample.

High radiation fields under post-accident conditions may present a problem with respect to worker safety at the sample extraction location. High ambient temperatures may also be a problem in some cases. Either of these situations may dictate longer transport lines than normally needed to accommodate installation of the sample collection and detection equipment at a properly shielded and air conditioned location.

If the contaminants are in the form of condensible vapors or reactive gases, long transport lines and large temperature changes in the sample or the transport line shall either be avoided or measures shall be taken to minimize potential loss of sample. Heat tracing of the transport line is readily accomplished, but conditioning of the sample may be necessary, such as a deliberate temperature change and purposeful dilution with a carrier gas.

In the case of particulate contaminants, the concerns about losses to the walls of the transport lines dictate keeping sample lines short. Abrupt temperature changes and abrupt cross-sectional reductions also should be avoided. The sampling location should be such that these constraints can be accommodated. This usually requires that the analysis or collection components be located near an acceptable sample extraction point, where the latter is chosen on the basis of completeness of particle mixing in the effluent stream. The attendant environmental requirements for the collection or analysis system must be applied. Previously described worker safety issues, which are related to high temperature and radiation fields, also apply. Concern for worker exposure to hazardous conditions may also arise when considering whether a transport line system can be made shorter or simpler to avoid particle losses. A potential exists for conflicting concerns in such decisions.

5.2.2 Qualifying the sample extraction location

Because the intent of sampling and monitoring stack effluents is measurement of contaminant discharge from the source, the sample extraction process should occur downstream of all inputs and control equipment. Within constraints imposed by more general considerations of an extraction site location on a stack, the site must be chosen to provide a valid representative sample of the entire contaminant discharge. Bends, fans, and duct junctions may produce distortions in velocity and contaminant profiles and may introduce angularity in the flow that can adversely affect samp- ling nozzle performance. Therefore, such locations should be avoided.

Both ANSI N13.1 (1969) and 40 CFR 60, Appendix A, Method 1 set rules for locating the sample extraction plane a required number of duct diameters downstream and upstream of the nearest disturbance in flow. However, due to facility or other constraints, sampling objectives often cannot be met by the application of such rules, and alternative approaches (which appear to violate them) may provide superior results. Yet, these do provide useful guidance for suggesting possible candidate sampling plane locations. This Standard requires that candidate sampling plane locations be qualified according to the following performance criteria.

5.2.2.1 Angular or cyclonic flow

At the proposed sampling location the flow of particles and gases shall not exhibit excessive angularity or swirl. The presence of swirl can adversely affect the mixing of particles in the effluent and degrade the performance of a sample nozzle. The criterion of acceptability is that the average flow angle shall not exceed 20 degrees (relative to the long axis of the stack or duct). An appro- priate method for determining if a proposed location meets this criterion is described in 40 CFR 60, Appendix A, Method 1, Section 2.4, "Verification of the Absence of Cyclonic Flow." If there is excessive flow swirl, it can be corrected by using internal elements placed in the stack or duct. In the past it was common practice to use either honeycomb or parallel plate flow straighteners. However, such elements shall be used only after suitable mixing of contaminants has been

1   achieved. In some situations excessive flow swirl can be eliminated through the use of static flow
2   mixing elements rather than flow straighteners.
3
4   **5.2.2.2 Contaminant concentration and velocity profiles**
5
6   If aerosol particles can be present in the flow, the criterion to be applied in establishing the accept-
7   able uniformity of contaminant mixing and velocity across a large diameter (> about 0.3 m) stack is
8   that the coefficient of variation (*COV*, the standard deviation as a percentage of the mean) of
9   concentration of 10 μm AD tracer aerosol particles and of a tracer gas (e.g., helium, sulphur hexa-
10   fluoride, or an already present contaminant gas) shall be less than or equal to 20% across the
11   center two-thirds of the cross-sectional area of the stack or duct. Measurement points at the
12   candidate sampling location should be selected in accordance with 40 CFR 60, Appendix A,
13   Method 1. For small diameter (< about 0.3 m) stacks or ducts, the measurement points shall be
14   selected in accordance with 40 CFR 60, Appendix A, Method 1A. It may be necessary to add
15   additional measurement points to obtain suitable mapping over the center two-thirds of the duct
16   area. Similarly, the *COV* of gas velocity shall be within ±20% across the center two-thirds of the
17   area of the stack or duct.
18
19   If only gaseous contaminants can be present, the criterion for the aerosol *COV* is not applicable.
20   Because the velocity is zero at the wall of the duct and gradually increases in the boundary layer of
21   a stack or duct, it is physically impossible to have a perfectly uniform velocity profile even in highly
22   turbulent flow. Ideal velocity profiles monotonically increase from the wall to the center of a duct.
23   An ideal particle concentration profile will have a shape similar to the velocity profile and will,
24   therefore, not be perfectly uniform. However, there should not be any large spike-shaped devia-
25   tions or distortions of the profile shape. Anomalously high concentrations of gases or aerosols can
26   occur in stack flows due to a variety of causes, including contaminant injection into the flow
27   boundary layer. Accordingly, an additional mixing criterion is that at no point in the measurement
28   grid shall the concentration of tracer gas exceed 30% of the mean concentration value in that
29   sampling plane. Because of the physical size of the nozzle, the measurement of the concentration
30   of 10 μm AD aerosol particles is difficult and subject to errors in the vicinity of the wall of a stack
31   or duct. Consequently, the 30% criterion is not applicable for aerosol particles.
32
33   The above 20% and 30% *COV* criteria of uniformity are selected to reflect the reality of experi-
34   mental errors expected in sampling from stacks in the field. The 10 μm AD test aerosol particle
35   diameter was selected because of the need for a test aerosol whose aerodynamic behavior clearly
36   exhibits inertial effects that could adversely influence mixing; because it has been previously used in
37   the performance specification of sample nozzles and transport lines (Rodgers 1987; McFarland et al.
38   1989); because it is relatively easily generated in either monodisperse (single particle size) or
39   polydisperse forms and released into stack flow; and because it can be present in stacks and ducts
40   of the nuclear industry (Rodgers 1995).
41
42   Often nuclear facilities have multiple stacks or ducts that are of similar design. For such situations,
43   it is not necessary to completely test the sampling location in a candidate stack or duct for compli-
44   ance with the requirements given in clause 5.2.2 provided that:
45
46   1) A geometrically similar stack or duct (one with proportional critical dimensions) has been
47   tested and the sampling location has been found to comply with the requirements of clause 5.2.2.
48   Critical dimensions are those associated with components of the effluent flow system that can
49   influence the degree of contaminant mixing the velocity profile. The prior testing may be
50   conducted either on a stack or duct in the field, or it may be conducted on a scale model.
51
52   2) The product of mean velocity (see equation A-2) times hydraulic diameter (as defined in

40 CFR 60, Appendix A, Method 2) of the candidate stack or duct is within a factor of four of that of the tested stack or duct.

3) The velocity profile in the candidate stack or duct meets the requirements of clause 5.2.2.2.

4) The velocity COVs of the two systems do not differ by more than 5%.

5) The sampling location in the candidate stack or duct is placed at a geometrically similar location to that in the tested stack.

If these requirements are fulfilled, the second location is acceptable.

If the requirements of clause 5.2.2 are met, sampling may be conducted at a single point. The nozzle shall be placed within the center one-third of the cross sectional area of the stack or duct at the qualified location.

5.3 Methods for qualifying the sample extraction location

To meet the contaminant mixing criteria given in clause 5.2.2, it is necessary to verify that the stream is well mixed or otherwise sufficiently described to establish that a sample of the effluent will be representative. When tests are conducted with a tracer gas, e.g., sulfur hexafluoride, the gas should be introduced downstream of the last location at which contamination can enter the effluent stream. If there is a fan that draws air from a bank of HEPA filters, and subsequently discharges the air into the stack or duct, the injection location can be between the HEPA filters and fan. Tests should be run with a tracer introduced at five or more locations across the cross section of the air stream. For a square duct the introduction shall be at the center and near (within a distance of 25% of a hydraulic diameter) each corner. For a round duct the introduction shall be at the center and near (within 20% of a diameter) the walls at the ends of perpendicular diameters. Sampling of the tracer gas shall be conducted across the cross sectional plane at the proposed sampling location.

The degree of mixing for aerosol particles shall be tested with particles of 10 μm AD, or the largest size expected if there can be a significant fraction of the aerosol mass or activity associated with sizes larger than 10 μm AD. The aerosol needs to be introduced at only one location, which is at the center of a stack or duct as far upstream of the sampling plane as possible, yet downstream of feeder ducts, fans, and filters. As in the case of a gas, the particles are demonstrated to be well mixed by sampling over the cross section at the proposed sampling location.

Testing to establish the degree of mixing requires sufficient gas or particles to provide an adequate signal at the extraction point. The method of detection and its detection limit are the important considerations in the amount of material introduced. Sufficient material must be introduced to be detectable after dilution in the effluent stream. Methodology for obtaining data on velocity, tracer gas and aerosol profiles is given by Rodgers et al. (1994).

It is essential to establish confidence that a chosen location for sample extraction based on demonstrated complete mixing using the above methods and criteria will continue to meet mixing performance requirements under changed conditions relative to those at the time of testing. Historical records of effluent flows can be used to provide evidence of extremes (high or low) of flows that might be encountered in a stack. Calculations of expected flows under accident conditions or very different operating modes can be based on documented engineering judgement. If possible, the continued acceptable performance of the sample extraction location with regard to mixing should be verified at higher and lower extremes of effluent flows by adding or removing

contributions to the effluent or fan operating speed. If mechanical mixing elements are used in the stack to achieve mixing performance, the results of tests and calculations derived from their design can provide an added basis for predicting performance under changed flow conditions. The results of engineering analysis and/or qualifying tests of flow angularity, contaminant concentration, and velocity profiles per the performance requirements of subclause 5.2.2 under changed conditions of flow (higher and lower) shall not differ from the test results under normal conditions by more than 5%. The goal of these determinations is a documented basis for confidence that the qualification of the sampling location will not degrade under reasonably anticipated changes in the effluent.

5.4 Sampling locations other than final effluent streams

Sampling may be required at locations upstream of the final exhaust discharge point for purposes of monitoring process conditions, personnel protection, or aiding the interpretation of measurements of the final exhaust. The sampling performance criteria for these situations may be the same as for normal final exhaust sampling; however, these conditions may be more extreme because higher concentrations, larger particle sizes, or more reactive or corrosive gases may be expected.

5.5 Designing effluent discharge systems for sampler placement

Accommodating sampler placement is an effluent system design and construction requirement. Such design shall include provisions for extracting a representative sample and for supporting transport and collection equipment in a manner that ensures the extracted sample is transported and collected with minimal loss for all contaminants. The most important requirement for extracting a representative sample is that the sampling plane shall be located where the effluent is well mixed. Other considerations to include in the effluent discharge design are as follows:

— do not add another effluent to the stream beyond the sampling point;

— do not locate the final emissions sampling point upstream of any effluent attenuation devices;

— include a section upstream of the sampling plane where corrective devices such as mixing elements could be easily installed;

— locate the sampling plane downstream of devices that promote mixing of the contaminants;

— avoid the use of flow straighteners except after the contaminants are well mixed and only to remedy angular or cyclonic flow;

— locate the sampling plane close to the collector or analyzer to ensure that transport lines are short and have few bends and transitions;

— provide ample access to service and maintain the sampling system and to install any needed shielding;

— provide for a stable electrical supply, environmental conditioning, and low levels of vibration;

— provide ample access ports for visual inspection of the nozzle, flow transmitter verification, and sampler performance testing.

The conditions of the effluent stream may provide an indication that the stream is well mixed. An obvious indication of being well mixed is that the extraction point is downstream of a mixing device such as a fan. Devices that will aid mixing include bends, a mixing plenum receiving one or more

streams, baffles that promote mixing, or a turbulent stream in a long length of duct. Nevertheless, conditions within the devices or combination of devices may be such that streaming occurs or that separation is induced. Highly cyclonic flow can inertially separate large-sized particles (those with sizes on the order of several μm AD or larger), or a temperature profile could cause condensation, Stephan flow, or thermal density effects. Flaws in the emission control devices or physical or chemical conditions in the devices can induce streaming.

6 Sampling system design

Regulations may require reporting emissions in either standard or actual velocities and densities whereas instrumentation may be calibrated in either standard or actual. Care must be taken when making measurements and reports that one is aware of both the regulations and the quantity measured so that appropriate units are reflected. The following discussion cannot accommodate all possible situations and may be adjusted for particular situations where regulations or instrumentations differ.

A graded approach is recommended to design systems that fulfil the requirements for sampling radionuclides in stacks and ducts of the nuclear industry. If the source is Potential Impact Category (PIC) Category 3 of table 2, only periodic confirmatory sampling is needed. Such measurements shall be carried out following either this standard, EPA Methods 5 or 17 (40 CFR 60), or through use of other procedures that can be demonstrated to have an accuracy equal to or exceeding that of Methods 5 or 17. If the source is either a PIC 1 or a PIC 2 of table 2, continuous monitoring of the effluent air is required. The focus of this clause is upon continuous monitoring requirements.

6.1 Bulk stream volumetric flow measurement

Accurate measurements of the flow in stacks and ducts shall be provided because the accuracy of any emissions estimate is directly related to the accuracy of flow measurements.

6.1.1 Requirements

The flowrate of air exhausted through a stack or duct shall be periodically measured and may need to be continuously monitored if there is a potential for significant emissions. For effluents that fall into PIC 3 of table 1 with a minor potential for emissions, only periodic confirmatory measurements of flowrate may need to be performed. Continuous flowrate monitoring shall be performed unless the source is minor in nature (PIC 3), or if the flowrate through a PIC 2 stack or duct is not anticipated to vary by more than ±20% during a year. Such factors as fan maintenance, the opening of doors, and the variations in the number of fans shall be taken into account in determining the need for continuous monitoring of flowrate. Effluent flowrate shall be continuously monitored if the stack or duct is a PIC 1 category source.

If continuous monitoring of flowrate is not required, annual measurements of flowrate shall be performed following the requirements of 40 CFR 60, Appendix A, Methods 1 and 2 subject to the modifications in annex A of this Standard, or other methods that can be demonstrated to have equivalent or better accuracy. The modified Method 1/Method 2 will be denoted hereafter as the Reference Method.

For stacks and ducts that must be continuously monitored, the flow measurement and recording system shall be capable of determining the mass flowrate of the effluent stream with an accuracy that is within 10% of that measured with the Reference Method. Here the mass flowrate is defined as the volumetric flowrate based on a pressure of 760 mm Hg (101.3 kPa) and a temperature of

25°C (298 K), and is given in units of m^3_{std}/s (or m^3_{std}/min). The use of these standard conditions is of value in dealing with sampling system data; however, in other topical areas of health physics such as dose assessment, the use of actual conditions may be more appropriate.

Any continuous flow monitor shall be subjected to annual accuracy audits. Performance of the unit shall be compared against the Reference Method. If the sensor of the continuous flow monitor is based on electronic or acoustical principles, automated daily checks of the instrument zero and span (or linearity) shall be made.

6.1.2 Apparatus and applications

Three types of systems are currently used for monitoring flowrates in stacks and ducts: thermal anemometers, pitot tubes, and acoustic meters. Other methods may be used if their accuracy is within the limits specified in clause 6.1.1.

6.1.2.1 Thermal anemometers

The use of thermal anemometers is advantageous because they provide a readout that is independent of pressure and temperature and can be used directly to determine mass flowrate. Thermal anemometers should not be used if there is a possibility of condensed vapor being deposited on the sensing element. Also, if a background aerosol is present, the use of thermal anemometry is discouraged; however, a cleaning schedule may be set up if it can be demonstrated that the bias of results due to accumulation of debris on the nozzle will be less than 3% at the end of the interval of the cleaning schedule. Rakes (arrays of multiple sensors) of thermal anemometers are acceptable. However, the requirements of uniformity of velocity profiles stipulated in clause 4.2.2 accommodate the use of single point velocity determinations. When single point anemometry is used, a correction factor shall be established to relate average mass flowrate to the reading from the single thermal anemometer element. In some applications, it may be beneficial to deploy redundant (two) single-point thermal anemometry systems.

6.1.2.2 Pitot tubes

A pitot tube will provide a measurement of the velocity at a given point in the flow. Velocity, V (m/s), is calculated from

$$V = C_P \sqrt{\frac{2\Delta p}{\rho}} \tag{2}$$

where: C_P is a pressure coefficient;

Δp is the pressure difference between stagnation pressure and static pressure measured with the pitot tube (in units of Pa);

ρ is the air density (kg/m^3) in the stack or duct.

If a Prandtl-type pitotstatic tube is used, the pressure coefficient is unity. However, if an S-type pitot tube is used, the pressure coefficient must be validated using the procedure stipulated in the Reference Method.

The readings from a single point pitot tube can be correlated with the actual flowrate. Data from a single point pitot tube should be recorded at intervals not to exceed 10 min duration. For reporting

purposes, the actual volumetric flowrate through the stack or duct, q_a (m³/min), should be converted to standard conditions, q_{std}, from

$$q_{std} = q_a \frac{T_{std}}{T} \frac{p}{p_{std}}$$ (3)

where: T_{std} is the standard temperature (298 K);

T is the temperature in the stack (K);

p is the absolute pressure in the stack (kPa);

p_{std} is the standard pressure (101.3 kPa).

If the absolute pressure in the stack does not vary by more than ±5% during the course of a year (exclusive of variations in barometric pressure), and if the temperature in the stack does not vary by more than ±10°C during a year, average values of stack pressure and stack temperature may be used to calculate velocity. If the pressure and temperature variations are outside these ranges, pressure and temperature shall be continuously measured and a value of air density calculated and recorded at intervals that do not exceed 10 minutes. Velocity values shall be based on the calculated values of density.

A pitot tube should be inspected for the presence of deposits of contamination on an annual basis, or more frequently if the air is not HEPA-filtered. For some applications it may be necessary to perform daily instrument checks for assurance that there is no buildup of material on the ports of the nozzle. Such checks may be performed by measurement of the pressure associated with a given rate of backflow through the ports. During the annual inspection, the system must be checked for leaks. Leakage at average flow conditions must not affect the results of differential pressure by more than 1%.

6.1.2.3 Acoustic flowmeters

These devices measure the time for acoustic signals to travel between two transceivers placed on opposite sides of a duct and displaced axially from one another. Acoustic velocity is independent of pressure but does depend on the square root of the absolute temperature in a stack. The acoustic flowmeter should accommodate measurements of temperature and take those values into account when calculating the velocity.

Velocity measured by this device is an average over a single line across the stack and not an area average, where the latter measurement would allow direct calculation of flowrate. Thus, a correction factor must be established between the reading of the instrument and the volumetric flowrate through the stack. When such a correction factor is applied, the result will be the actual volumetric flowrate through the stack or duct, q_a. Through use of equation (3), the flowrate can be converted to that at standard conditions, q_{std}.

If the absolute pressure in the stack does not vary by more than ±5% during the course of a year (exclusive of variations in barometric pressure), and if the temperature in the stack does not vary by more than ±10°C during a year, average values of absolute stack pressure and stack temperature may be used in equation (3). If the pressure and temperature variations are outside these ranges, pressure and temperature must be continuously monitored. Values of flowrate at standard conditions will be calculated and recorded for intervals that do not exceed 10 minutes.

6.2 Nozzle design and operation for sampling aerosol particles

This method is applicable to sampling from stacks and ducts that have the potential to emit aerosol particles. This approach is based on experimental and theoretical evidence that extractive sampling from a single point in a qualified profile of duct flow where the flow is well mixed, with a properly designed nozzle, should provide a representative sample during normal conditions and an adequate sample during accident conditions.

6.2.1 Basic considerations

Inlet nozzles serve the function of removing a sample from the free stream of a stack or duct and rendering it compatible with transport to an analyzer or collector. Previously, the ANSI N13.1 (1969) standard recommended probe designs that had constant internal cross sections and a 90° bend of the same cross section. This is no longer considered good practice due to substantial aerosol particle losses in both the straight entrance region and the bend, and due to errors associated with off-design operational conditions (Fan et al. 1992; McFarland and Rodgers 1993). Also, ANSI N13.1 (1969) recommended the deployment of multiple nozzles in circular ducts larger than 6-in. (152 mm) diameter or in rectangular ducts with cross-sectional areas greater than 0.5 ft^2 (0.046 m^2). For larger ducts, as many as 20 nozzles were recommended, with rakes (several nozzles on a common manifold) of such nozzles spanning the stack or duct. The use of these rakes is no longer considered good practice because for a given flowrate, smaller nozzle inlet diameters must be used as the number of nozzles is increased to accommodate the ANSI N13.1 (1969) recommendation of isokinetic (air velocity at the nozzle inlet plane matching that of the free stream air velocity) sampling. The use of large numbers of small nozzles exacerbates sampling deficiencies inherent in the ANSI N13.1 (1969) nozzle design.

In place of multiple point sampling, single point representative sampling should be used, with the requirement that both fluid momentum and contaminant mass are well mixed at the sample extraction location in the sampling plane as specified in the performance criteria of clause 5.2.2.2. Also, the ANSI N13.1 (1969) recommendation for isokinetic sampling is no longer required. Recent studies have shown that isokinetic operation is not a prerequisite for obtaining representative samples (McFarland and Rodgers 1993).

The design and use of an extractive aerosol sampling nozzle can have a significant impact on the quality of a sample. There are two basic factors by which an nozzle can produce a nonrepresentative sample: 1) operation in such a manner that the aspiration ratio, A, is not unity, and 2) losses on the internal walls of the nozzle, Wl. The two terms, aspiration efficiency and wall losses, are defined as

$$A_e = \frac{c_i}{c_\infty} \tag{4}$$

and

$$Wl = \frac{c_i - c_e}{c_i} \tag{5}$$

where: c_i is the concentration at the nozzle inlet plane;

c_∞ is the aerosol concentration in the free stream;

c_e is the concentration at the nozzle exit plane.

In evaluating the effectiveness of a sampling nozzle, both the aspiration ratio and wall losses should be considered. Their effects are manifested in the transmission ratio, T_r, which is the ratio of the aerosol concentration at the nozzle exit plane to the aerosol concentration in the free stream, as in

$$T_r = \frac{c_e}{c_\infty} \tag{6}$$

The transmission ratio, aspiration ratio, and wall losses are related by

$$T_r = A_e(1 - Wl) \tag{7}$$

Although all three parameters are important, the performance of a nozzle is best described in terms of its transmission because that parameter provides a measure of the amount of aerosol that actually penetrates from the free stream to the exit plane of the nozzle.

6.2.2 Nozzle performance

A sampling nozzle shall have an aerosol transmission ratio within the range of 0.80 to 1.30 over the entire range of normal or anticipated accident operational conditions for an aerosol particle size of 10 μm AD, or for the range of sizes that could be encountered in normal operating or accident conditions if those sizes are greater than 10 μm AD. Also, the aspiration ratio of a sampling nozzle shall be within the range of 0.80 to 1.50 for the anticipated range of operating conditions and the previously noted particle size or sizes. Compliance shall be demonstrated with liquid aerosol particles, which will provide conservative transmission values in comparison with solid particles because liquid particles adhere to walls, while solid particles may rebound or be re-entrained from a collection surface.

6.2.3 Nozzle designs

When a nozzle is operated isokinetically, the aspiration ratio is unity; however, the wall losses can cause the transmission to be considerably lower than unity. Fan et al. (1992) wind tunnel tested an elbowed nozzle with a nearly constant internal diameter designed in accordance with ANSI N13.1 (1969). They found the wall loss ratio was approximately 75% for 10 μm AD aerosol particles at isokinetic conditions over a range of stack velocities. In addition, when a nozzle is operated at off-design conditions, the transmission ratio can be affected. These conditions can be produced by variations in the free stream velocity, by variations in sampling flowrate, and by a nonparallel orientation of the nozzle with the flow direction. The latter factor can be caused by nozzle misalignment or flow swirl. Performance of ANSI N13.1 (1969) nozzles and the rakes of such nozzles are affected by all of these factors.

Modern nozzle designs have better performance characteristics than the original ANSI nozzles. McFarland et al. (1989) and Chandra and McFarland (1995) have developed shrouded nozzle designs that considerably reduce wall losses. An example of a shrouded nozzle that was designed for use in stack sampling in the nuclear industry is shown in figure 2a. The transmission of

1   10 μm AD aerosol through the nozzle as a function of free stream velocity is shown in figure 2b. In
2   general terms, the wall losses for 10 μm AD aerosol particles are about one-fifth of those of the
3   ANSI N13.1 (1969) nozzles tested by Fan et al. (1992). The shrouded nozzles are designed to be
4   compatible with single-point sampling, where the sampler is operated at a constant flowrate with
5   the flow velocity in the shroud being about 30% that of the nominal stack free stream velocity.
6   The transmission ratio for 10 μm AD aerosol particles is relatively unaffected by variations in stack
7   velocity, flowrate, free stream turbulence and angle between the free stream and nozzle entrance.
8   Williamson et al. (1987) and Chandra (1992) designed sharp-edged unshrouded nozzles that have
9   wall losses of 10 μm AD particles that are approximately half of those of the ANSI N13.1 (1969)
10   nozzles.

11

12   **6.2.4 Application and performance considerations**

13

14   The following factors should be considered in the selection and use of a sampling nozzle.

15

16   **6.2.4.1 Location**

17

18   Sampling should take place at a location where both the aerosol concentration and fluid momentum
19   (velocity) are well mixed and thus meet the performance criteria of clause 5.2.2.2.

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21   **6.2.4.2 Orientation**

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23   For aerosol sampling, the nozzle axis should be aligned parallel to the temporal mean flow stream
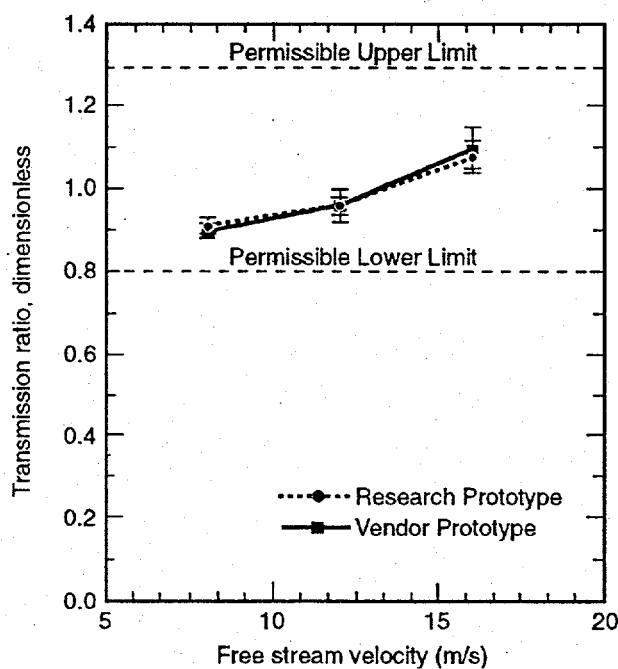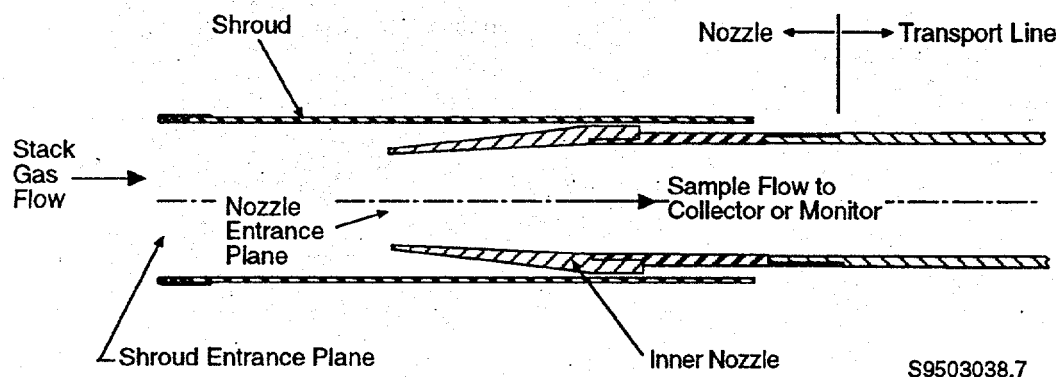24   direction.

25

26   **6.2.4.3 Transmission and aspiration ratios**

27

28   The transmission and aspiration ratios of the selected nozzle design shall be traceable to experi-
29   mental verification of performance for conditions that include the nominal sampling flowrate and
30   range of anticipated sampling flowrates, the nominal free stream velocity and the range of
31   anticipated free stream velocities, and a particle size of 10 μm AD. If actual testing is used, the
32   means for determining the transmission and wall loss ratios shall be documented. If reference to
33   previous testing is employed, the equivalency of the selected design and the design that was tested
34   shall be demonstrated.

35

36   **6.2.4.4 Sampling flowrate and free stream velocity**

37

38   During operation of a nozzle, the sampling flowrate may be varied to accommodate changes in the
39   free stream velocity, or it may be held constant to accommodate the requirements of the collector
40   or analyzer. However, for record samples, if the source is PIC 1 of table 1, the sampling flowrate
41   shall be varied in proportion to the flowrate through the stack or duct in order to permit an accurate
42   assessment of the quantities of any releases. Continuous air monitor (CAM) samples in PIC 1
43   stacks or ducts may be operated at a fixed flowrate. If the sample flowrate is varied, the ratio of
44   the sampling flowrate to the stack flowrate shall be established for nominal operational conditions
45   of the stack or duct. Over the range of operational flowrates that is based on either historical
46   records or *a priori* considerations, the ratio should not vary by more than ±25%.

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Shroud

Nozzle ←→ Transport Line

Stack
Gas
Flow →

Nozzle
Entrance
Plane

Sample Flow to
Collector or Monitor

Shroud Entrance Plane

Inner Nozzle

S9503038.7

S9509031.2

Figure 2 — a) A shrouded nozzle designed for a sampling flowrate of 57 liter/min
(2 cfm). b) Results of wind tunnel tests showing transmission of 10 μm AD
aerosol particles through the nozzle of figure 2a. Sample flowrate was
maintained constant at 57 liter/min during these tests.

6.2.4.5 Nozzle configuration

The leading edge of the nozzle should have a sharp edge with the external cone angle not to exceed
30°. Other configurations may be used if experimental data show either equivalent or superior
performance to the sharp-edged nozzle. If the sampling nozzle is shrouded, the shroud should not
have a sharp leading edge. For sharp-edged nozzles, the leading edge of the nozzle should be

inspected for damage following installation and subsequent to any maintenance procedures in which the nozzle could be damaged.

6.2.4.6 Rakes

While the use of a sampling rake is discouraged, if one is used it shall be tested for aerosol transmission. Each of the nozzles shall meet the requirements contained in clause 6.2.2. In addition, the transmission of an aerosol through a rake shall be measured and documented. Either *in situ* or laboratory tests may be used in the testing procedure. If a rake is used for collection of samples for record purposes, the transmission of 10 μm AD aerosol particles from the free stream to the exit plane of the rake shall not be less than 80%. Flowrate through each nozzle in a rake shall be measured by an approach that does not affect the flow through other nozzles in the rake. The flowrate in any nozzle may not differ from the mean flowrate by more than $\pm 10\%$.

6.2.4.7 Materials of construction

Nozzles shall be constructed of materials that will not react with either the aerosol or the vaporous constituents of the gas stream. Surface roughness of the internal regions of nozzle that contact the sampled stream should not exceed 32 micro-inches. The surface roughness of the external region of the sampling nozzle from the inlet plane to a distance of two nozzle inlet diameters from the inlet plane should not exceed 64 micro-inches. A shroud should have a surface roughness that does not exceed 128 micro-inches.

6.2.4.8 Maintenance

The sampling nozzle shall be checked annually for alignment, presence of deposits of foreign materials and other factors that could degrade the performance of the sampling system. If there are background aerosols that can produce deposits, a cleaning schedule should be established that will not allow over 5% of the inlet area of a nozzle to be occluded. For nozzles that are used to sample HEPA-filtered air, the nozzle should be cleaned if there are visible deposits of material on either the internal or external regions of the nozzle.

6.2.4.9 New concepts

When new approaches are developed for design and operation of nozzles, such designs may be used in ducts and stacks if it can be demonstrated experimentally that the designs meet, or exceed, the performance specifications given in clause 6.2.2. The test conditions should include experiments to determine the wall losses and aerosol transmission at conditions of 1) particle sizes of 3, 10, and 20 μm AD at the nominal free stream velocity and nominal flowrate; 2) maximum and minimum operational or anticipated free stream velocities for a particle size of 10 μm AD at the nominal sampling flowrate; and 3) maximum and minimum anticipated sampling flowrates for a particle size of 10 μm AD at the nominal free stream velocity.

6.3 Sample transport for particles

The transport of aerosol particles from a sampling nozzle to a collector or analyzer shall take place in such a manner that changes in concentration and size distribution of airborne radioactive materials are minimized within the constraints of current technology.

6.3.1 Depositional losses

The deposition of particles inside the transport tubing shall be evaluated either through experimental

techniques, documented and referenced hand calculations (Brockman 1993), or through use of documented computer codes (e.g., Anand et al. 1993) for either 10 μm AD aerosol particles or the size range expected in the particular application under normal, off-normal, and anticipated accident conditions.

The straight sections of transport tubes, particularly horizontal tubing sections, should be kept as short as possible, and the number of bends should be minimized within the geometrical constraints of the application. There should be no inward facing steps at the tubing connections. The tubing ends shall be free of burrs and crimping. For record samples, it is recommended that not more than one 90° bend be used, although it is recognized that there may be situations where more bends may be necessary. Bends shall have a curvature ratio (radius of curvature of the bend divided by the tube diameter) of at least 3.0. Flattening of the bend caused by a bending process shall not exceed 10%, where flattening is defined in terms of the major and minor axes of the tube cross section at the angular midpoint of the bend. As an example, the diameters of a 90° bend would be measured at the 45° location. The ratio of the maximum tube diameter to the minimum tube diameter shall not exceed 1.1. The user should note that special fabrication techniques may be required to meet these specifications.

In general terms, there will be some losses of aerosol particles in transport lines, and any design will entail compromises. The design parameters shall be carefully chosen to optimize the utility of the overall system. The penetration of 10 μm AD aerosol particles from the free stream to the collector or analyzer should be known and should not be less than 50%. Annexes B and F provide guidance on assessing particle penetration.

6.3.2 Corrosion

The internal walls of the transport system shall be constructed of materials that are minimally reactive to inadvertently deposited aerosol particles or to reactive vaporous compounds that could be present in the sample. The materials of construction for external walls and seals between sampling system components should also be compatible with the environment to which they are exposed. Materials recommended for the nuclear industry are stainless steel for general applications and tetrafluoroethylene for radioiodine.

6.3.3 Electrostatic effects

If plastic is used in aerosol transport systems, internal electric fields can cause particle losses (Charuau 1982); in particular, plastic tubing that has been flexed can show abnormally high wall deposits (Liu et al. 1985). A transport system should be constructed of materials such as metals or conductive plastics that will not sustain internal electrostatic fields. In many applications it is useful or convenient to use flexible nonmetallic tubing to connect a sampler or analyzer to a transport line, particularly if there is need to isolate an analyzer from mechanical vibrations in the sample transport line. The inside diameter of the plastic line should not be smaller than the inside diameter of the components with which it is connected and the bend curvature ratio should not be less than a ratio of three, nor may the curvature of a bend cause more than a 10% change in the inside diameter of the tube. If nonconductive flexible tubing is used, the line length exposed to the sample should not exceed two times the internal diameter of the tube.

Of the flexible tubes that can be categorized as nonconductors, neoprene or natural rubber is recommended to minimize electrostatic deposition of particulate matter (Charuau 1982). If radioiodine is present in the effluent stream, materials suggested in annex C should be used.

6.3.4 Smoothness of internal surfaces

To minimize aerosol depositional losses and to facilitate decontamination, the internal surfaces of transport lines should be as close to hydraulically smooth as practical. Drawn tubing or other types of tubes with ϵ/d_t less than approximately 5×10^{-6} are acceptable, where ϵ = height of surface roughness of the internal tube walls and d_t = tube diameter. This criterion requires a surface finish of approximately 64 micro-inches or less for tube sizes that are on the order of 1 in. in diameter. Fittings between tube components should not have steps that cause an abrupt reduction in diameter of the flow.

6.3.5 Condensation

Condensation of vapors in transport lines, collectors, and analyzers must be avoided. Condensation takes place when the temperature of air in the transport line is less than the saturation temperature of the vapor of interest. Thermally insulating, and in some cases heating, the transport line may be required to prevent condensation. For situations in which heating of the sampling line may result in unacceptably high temperatures at a collector or analyzer, a dilution system should be considered; however, care must be exercised to ensure that the dilution process does not produce condensation at the mixing location. Experimental or numerical analyses shall be performed to demonstrate the effectiveness of any design provisions that are intended to minimize or preclude the formation of condensation in sample transport systems.

6.3.6 Cleaning transport lines

An additional consideration at some facilities is the need for cleaning transport lines. For applications in which the sampled air is HEPA-filtered, there may not be a need for cleaning within the expected lifetime of the installation; however, for applications where background aerosols are present, periodic cleanout may be necessary. As a minimum, for systems that sample HEPA-filtered air, inspections for deposits should be made annually. If there is an indication of deposits inside the nozzle inlet, then the transport line shall be inspected. If deposits are visible inside the transport line, the line shall be cleaned. For systems that sample nonHEPA-filtered air containing background aerosols, if an estimate can be made of the rate of deposition of all aerosol particles on the internal walls of the system, the system should be cleaned when the mean mass of deposited material exceeds 1 g/m². Alternatively, a cleaning schedule can be set up based on performance of the transport system. The interval between cleanings should not exceed that during which accumulations of wall losses will cause the overall penetration of 10 μm AD aerosol particles through the sampling system to be reduced by more than 10%. In addition, if there are indications of re-entrainment of deposits from the walls of the sampling system or if there has been sampling of easily re-entrainable aerosol particles (e.g., flakes), either of which could cause anomalous radiological data to be gathered, the system should be cleaned. Decontamination requirements must be taken into account in any cleaning procedure.

6.4 Gas and vapor sample extraction and transport

Much of the above discussion applies generally for sampling particles and gases; however, special consideration shall to be given to extracting and transporting vapors and gases to determine where special system design may be required.

When nonreactive gases and vapors are the only species being sampled, the sampling requirements are considerably simpler than those for aerosol particles. The requirements for minimizing particle line-loss are irrelevant. Deposition in long transport lines and condensation due to temperature changes in the line must be avoided. If the flow can contain only gaseous contaminants, the nozzle

design is not critical, but the sampling shall take place at a location where the flow is well mixed and meets the criteria of clause 5.2.2.2. The nozzle design can be simplified to an open ended or perforated tube. The extraction and transport requirements that still apply include extracting the sample from a well-mixed location and avoiding water and vapor condensation in the transport and collection system (except where condensation is used as the collection method).

When nonreactive gases, vapors, and particles are being simultaneously sampled, the particle sample extraction and transport requirements shall apply, which will also ensure adequate delivery of the gas and vapor sample. The remaining consideration then is the selection of the appropriate collection devices. It may be appropriate to locate the gas or vapor collection device downstream of a particle filter to eliminate potential radionuclide interferences by particulate matter.

When working with reactive gases and vapors, particular attention must be paid to the sampling system construction materials and to the avoidance of condensation. The construction material should have minimum reactivity with the gas. Consideration shall be given to the advantages of providing a separate sampling system for the gases whenever the construction materials that would be desirable for the transport of the particle and gas samples are incompatible. In situations where even a low level of reactivity cannot be avoided, the transport line length shall be kept to a minimum. The penetration of the gas or vapor through the complete extraction and transport system shall be documented. The minimum transport efficiency for vapor or gas samples from the free stream to the collector/analyzer should be 50%. If long transport lines are unavoidable, consideration shall be given to the effect of transport and detection delay time caused by deposition, chemical transformation and subsequent resuspension. Careful consideration should also be given to how significant an effect the delay has on the timeliness, interpretation, and usefulness of the resulting data. Although rapid changes in the emission may become smeared over a large time interval relative to the change in emission, the data may still be useful and quantitative when interpreted in that light. Annexes C and H provide guidance on the sampling of radioiodine and tritium and annex F provides guidance on verifying the transport of sampled constituents.

6.5 Collection of particle samples

6.5.1 General considerations

Depending on the purpose of the sample, a wide range of techniques are available for monitoring or collecting airborne particles (see, for example, Hering 1989). Particles can be collected on filters for retrospective determination of total mass, radioactivity, or chemical form; in aerosol cyclones or cascade impactors for determination of particle size distribution; on electron microscope substrates for determination of particle morphology; or they can be observed by light-scattering or time-of-flight techniques for monitoring of number concentration and size. Realtime devices such as alpha continuous air monitors (CAMs) typically collect particles on a filter or impaction substrate and monitor the accumulation of radioactivity with time. Critical issues for selection and operation of particle collection devices are:

— appropriate presentation of the sample for realtime analyses or preservation of the sample for retrospective analyses;

— adequate flowrates and detection efficiencies to meet sensitivity requirements;

— minimal inleakage within the collector;

— minimal particle loss within the collection zone.

6.5.2 Filter media

Filters are porous structures with controlled external dimensions such as thickness and cross sectional area normal to the flow. Filtration is the most widely used technique for collection of aerosol particles because of its low cost and simplicity of use. Filters capture particles by a combination of physical processes, which include direct interception, inertial deposition, Brownian diffusion, electrical attraction, and gravitational sedimentation. As shown in figure 3, filters typically have a minimum collection efficiency for particles that are approximately 0.2 - 0.5 μm diameter. Above about 0.3 μm diameter, filtration efficiency increases due to inertial impaction and below this size efficiency increases due to Brownian diffusion.

A common misconception is that filters act as sieves, and that there is a direct relationship between the pore size of a filter and the minimum particle size that can be collected. In reality, because collection occurs by a complex combination of mechanisms, filters with nominal pore sizes larger than 1 μm can be very efficient collectors of sub-micrometer particles. As demonstrated by Lindeken et al. (1964), membrane filters show no serious degradation of collection efficiency until the pore diameters exceed 5 μm. In fact, filters with a 5-μm pore size are often preferred because they have lower pressure drops than smaller pore-size filters, yet retain high efficiency values.

Many filter media are available for use in collection of aerosol particles (see, for example, Liu et al. [1983] and Lippman [1989]). Materials include cellulose, glass, quartz, and plastic fibers. Sintered structures of metals or mineral particles have been used for high temperature filtration. Users are cautioned to be selective in their choice of filter media. Selection should be based on careful consideration of collection efficiency for the typical particle size in the duct, the area of the filter, the pore size, the filter's resistance to air flow, the background radioactive material of the filter, filter fragility, cost, self-absorption within the filter, and chemical solubility. If the performance
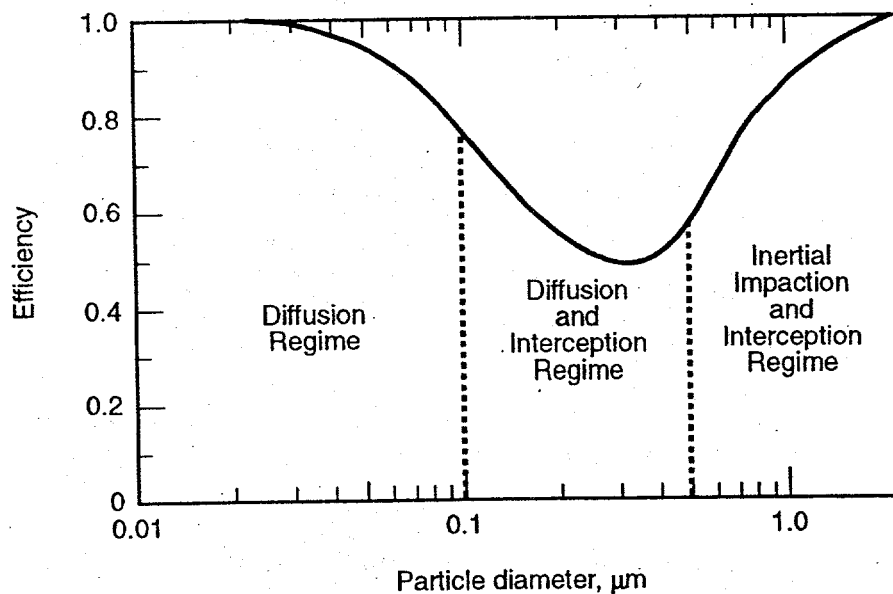
S9509031.5

Figure 3 — Schematic of filter efficiency versus particle size illustrating the different filtration regimes (Lee and Ramamurthi 1993).

characteristics of the front and back surfaces of the filter are not within 5% of each other for the intended purpose of the sample, there shall be a readily accomplished means of identifying the appropriate surface for particle collection. The filter shall be strong enough to maintain integrity at the required sample flowrates and during handling activities. If a filter and sample must be separated for a particular analytical method, the user should select a filter medium that can be easily dissolved by a method that will not attack the particles of interest. In other cases, it may be imperative that the sample be collected on the surface of the filter rather than imbedded in the filter. Higby (1984) has demonstrated that absorption of alpha radiation emitted from airborne particles collected on glass-fiber filters does not constitute a major source of error in estimating concentrations of airborne alpha-emitting radionuclides, but excellent resolution in alpha spectroscopy requires use of membrane-type filters which are front-surface collectors.

Decisions on upgrading to more modern filter media should include additional considerations, such as the potential loss of continuity between historical and future sampling results, potential impacts on vacuum system performance, requirements for analyzer retesting and requalification, requirements for revision and approval of documentation, retraining requirements for workers, and potential impacts on secondary uses of the filter samples, such as periodic chemical analyses for process control. However, some filter media date back many decades and their continued use is not justified simply because of historical precedents.

When filter media are used, a backup support that produces negligible pressure drop should be used behind the filter to prevent filter distortion or deterioration. The sample holder shall provide adequate structural support while not damaging the filter, shall prevent sampled air from bypassing the filter, should facilitate changeout of the filter, and should facilitate decontamination. If rubber gaskets are used to seal the filter to the backing plate, the gasket should be in contact with the filter along the entire circumference to ensure a good fit. Periodically, inspections of the gasket should be performed to detect degradation and eliminate buildup of dust or filter material, which could result in sampled air bypassing the filter. Monthly inspections may be sufficient.

To reduce the uncertainty associated with collection efficiency, filters that are used for sampling airborne radioactive particles should have a minimum efficiency of 95%. Efficiency values shall be applicable to the conditions of use. For example, the collection efficiency of a Whatman 41 cellulose fiber filter is 99.5% for 0.3 μm aerodynamic diameter when the face velocity is 124 cm/s, but drops to only 72% at a face velocity of 16.9 cm/s (Liu et al. 1983). If published or manufacturer's data are not available on filter collection efficiency for the particle sizes of interest, then the efficiency shall be determined by the user. This can be done by placing a highly efficient membrane or glass fiber filter behind the filter of interest and then comparing the mass penetrating to the backup filter to the total mass collected on the both filters (see Hickey et al. 1991). If a filter with an efficiency lower than 95% is required to meet the overall sampling objectives, then a correction for efficiency shall be made. Because filter efficiency is a function of air flowrate, care shall be taken to maintain a sample flowrate that is adequate to achieve the desired collection efficiency.

If penetration of radioactive material into the collection media or self-absorption of radiation by the material collected would reduce the count rate by more than 5%, a correction factor should be used. A dual filter method can also be used to measure efficiency absorption in the filter medium (Hickey et al. 1991). Evaluation of self-absorption in the material collected may require separate radiochemical analyses.

Annex D illustrates the type of information that is useful in selecting an appropriate filter for sampling airborne radioactive particles. This includes physical and performance characteristics of a number of typical coarse-fiber, fine-fiber, and membrane-type filters.

1 ## 6.6 Collection of gas and vapor samples

2

3 Airborne radioactive volatile materials and so-called noble gases such as krypton are frequently
4 important contaminants, and their sampling and collection require techniques and methods differing
5 from those used in particle sampling. This topic may be divided into two general methods of
6 sampling: 1) sampling with retention of specific constituents of the airstream, and 2) sampling
7 without constituent separation. Annexes C and H provide further guidance specific for radioiodine
8 and tritium.

9

10 ### 6.6.1 Sampling with retention of specific constituents

11

12 Sampling with removal and collection of specific constituents requires a detailed knowledge of the
13 chemical and physical properties of the radioactive material of interest, including possible interfering
14 materials such as particulate matter and accompanying nonradioactive gases (e.g., acids and
15 organic chemicals). The many possible combinations of the properties of the constituents to be
16 measured and the accompanying airborne materials require careful study to select the optimum
17 collector. Gases and vapor components may be soluble in water, may be highly reactive with
18 certain solutions, may dissolve in specific nonaqueous solvents, or may be retained on specific solid
19 adsorbents or other specifically prepared media. In general, continuous rather than grab samples
20 are taken when separation and removal of a constituent is required. Sampling rates must be estab-
21 lished to ensure adequate sensitivity for the selected radioassay method and must be compatible
22 with the collector performance characteristics. The principal collection methods include solid
23 adsorbents (such as carbon, zeolites, silica gel, and metal beds), condensation, gas absorption, and
24 catalytic or chemical reaction. More detailed descriptions can be found in Brown and Woebkenberg
25 (1989).

26

27 ### 6.6.2 Sampling without constituent separation

28

29 In some instances a sample of air and all its contained radioactive constituents may be desired for
30 measurement of trends or relative levels of airborne materials. Examples are noble gas isotopes,
31 tritium, and activated gases near a reactor. Volume collection and flow-through detectors are the
32 two principal methods for total gas sampling or monitoring.

33

34 Because the constituent radioactive materials of interest may not be concentrated with a particular
35 flow-through or volumetric collection device, insufficient sensitivity of detection may limit or
36 preclude their use. Each situation will have to be evaluated individually to determine the feasibility
37 of the gross sample measurement.

38

39 Volume collection methods include the following:

40

41 — using an evacuated container that can be valved open to the stream of interest, then sealed
42 and returned to a laboratory for measurement of gross radioactivity or of individual constituents;

43

44 — passing the stream through the sample vessel until the vessel is completely purged, then
45 closing the inlet and outlet valves;

46

47 — pumping the sample stream into deflated bags (of a nonadsorbing material) for later
48 compression and analysis;

49

50 — compressing the sample stream into a vessel for realtime or subsequent analysis.

51

52 A flow-through sample vessel may also be an ion chamber whose ion current reflects the relative

radioactivity of material in the gas. Care must be taken to keep the gas well above its dewpoint in the sampling system and ionization chamber. A gradual buildup of contamination in the chamber should be expected. The effect will be manifest by a gradually increasing response with clean air in the chamber.

Flow-through chamber samplers may be similarly monitored by gamma ray scintillation crystal counters or other detectors held adjacent to or inserted in a well in the chamber wall. An increase background from contamination must be expected in these samplers, and the chamber must be periodically decontaminated to avoid errors from this source. Prior filtration of the airstream will assist in keeping the chamber clean when gaseous constituents alone are to be measured. A flow-through sampling system, which is frequently used at power reactors for accident monitoring, involves placement of a high- or wide-range detector mounted directly inside or outside the effluent stack or duct.

6.7 Sample volume measurement

The sampled volume of air is a key parameter in determining emission rates and dose levels. Because sample volume depends on the density of air, a standard density value should be selected for all data that are used to represent or report sample volume data at a facility. It is recommended that the standard density be based on dry air at a pressure of 101.3 kPa (760 mm Hg) and a temperature of 25°C (298 K). The total sampled volume at these standard conditions is represented by the symbol $Q_{T,std}$. Other pressure and temperature values may be employed in use of the data for calculating exposure levels; however, the density would be nonstandard and shall be so reported.

In general terms, if the stack or duct is PIC 1 of table 2, monitoring and control of the sample flowrate shall be used and the sample flowrate shall be varied in proportion to the flowrate through the stack or duct. For other PICs of table 2, the sample flowrate may be held constant.

6.7.1 Basic considerations

The flowrate through a sampling system shall be measured and an indication of the value must be displayed. However, if the flowrate is controlled at a set value (e.g., for PIC 2 and 3 systems of table 1), the display can be an error signal that the control system is out of compliance. The flow detector shall be placed in the flow system in such a manner that it does not cause losses of aerosol particles or reactive radioactive gases. As a consequence, the flow sensor is generally located downstream of the collector or analyzer. This sensor location generally causes the pressure at the point of measurement to be less than that in the stack or duct. Also, temperature at the point of measurement may differ from that in the stack, duct, or chamber from which samples are being removed.

6.7.2 Volume of air sampled

If the sampling flowrate will not vary by more than ±20% over the sampling period, as a minimum it should be recorded at the start and the end of a sampling period. For such a case, the total volume sampled, Q_T, may be calculated from

$$Q_T = \frac{q_1 + q_2}{2} \Theta \tag{8}$$

where: q_1 (liter/min) is the volumetric flowrate indicated by the flowmeter at the start of the sampling period;

q_2 (liter/min) is the volumetric flowrate at the end of the period;

Θ (min) is the time period over which sampling is performed.

Continuous flow measurement control shall be used for all stacks and ducts where significant emissions could occur (PIC 1 of table 1), or if the flowrate can vary by more than $\pm 20\%$ during the sampling period. When continuous flow measurement is employed, the flowrate should be recorded at intervals not to exceed 10 minutes. The total volume of sampled air is based on integration of flow over the entire sampling period. If the time interval between recordings is Δt (min), and the flowrate during the interval (either the true average in the interval, the average of the initial and final values in the interval, or the value at the interval midpoint) is q_i (liter/min), the total volume of air sampled (liter) is calculated from

$$Q_T = \sum_{i=1}^{N} q_i \Delta t \qquad (9)$$

Other integration schemes may be used if the numerically induced errors do not exceed those implicit in equation (9). The total sample volume, Q_T, is based on the flowrate indicated by the flowmeter. For many flowmeters, the indicated flowrate is not based on standard conditions, and appropriate corrections shall be made to the resulting data.

6.7.3 Flowrate control

If sampling is performed with constant sample flowrate conditions, where a controller is used to maintain constancy of flowrate, the flow controller shall maintain the flowrate within $\pm 15\%$ over conditions that correspond to an initial pressure drop across the collector (usually a filter) or analyzer to a value that is twice the initial pressure drop. The vacuum source used during a test of the controller shall have similar characteristics to the vacuum source used to draw air through the system in the field application. If the source is PIC 1 of table 2, a controller shall be used to maintain the ratio between sample flowrate and effluent flowrate within $\pm 20\%$ of a predetermined value.

6.8 Optimization and upgrading of new and existing systems

Even with complete awareness of the many conditions that contibute to obtaining a representative sample, the design will frequently be a compromise between the best location of the nozzle from a technical standpoint and safety and logistical considerations. Arriving at a suitable solution requires optimization among competing factors. Guidance on the process of optimization for radiological protection has been provided by the International Commission on Radiological Protection (ICRP 1989).

6.8.1 Defining the scope of the study

Optimization studies may address design issues covering all monitored stacks in a certain category (e.g., the use of a certain type of transport line and detector for all tritium stacks), or it may apply to specific stacks that require special treatment. If the design process is a prelude to new construction, it is usually easier to apply optimization globally to stacks in the same category. Retrofit of old facility stacks is more likely to involve stack-specific concerns and treatments. Once the scope of

the optimization study is defined, it is necessary to specify radiological protection factors, constraints on access, applicability of certain options to achieve good mixing, and many other factors and limitations that will affect the final decision.

6.8.2 Identifying options and their consequences

A number of options will have to be considered in each case, with the implications of their adoption considered with respect to their contribution (or detriment) to representative sampling performance, consequences for workers' safety, and other factors affecting the decision. In some cases it may be advisable to conduct, computational, laboratory, and/or field studies in support of the decision-making process. For example, it may be that a sample withdrawal location in an existing facility stack is unacceptable due to poor mixing, but is optimal in terms of accessibility, short transport lines, and worker safety and can be utilized if a simple, easily installed mixing system could be introduced. Computational fluids modeling, physical scale modeling, and *in-situ* measurements may provide effective solutions to complete the design of an optimized system.

6.8.3 Use of decision-aiding techniques

In many cases the results of an optimization study and a comparison among the options identified can be carried out qualitatively using straight-forward prioritization and ranking techniques. But in some cases quantitative techniques may have to be applied to balance dose implications and other factors such as occupational safety, existing facility constraints, and others. Adequacy of documentation and reliability of any estimation and prioritization procedures used shall be a major concern in either case and should enter into the record of decision.

6.8.4 Upgrading and retrofit of existing stacks

Many existing nuclear facilities have stack monitoring systems built during the 1960's through 1980's. They have sampling systems based on isokinetic sampling with multiple small-diameter nozzles. In addition, many facilities have flow systems that are fitted with flow straighteners, which serve the purpose of making the velocity profile uniform, but which impede mixing of contaminant mass in the flow stream. It is now known that if an aerosol contaminant is not well mixed, and a multitude of poorly designed, small diameter nozzles are deployed, seriously nonrepresentative samples may result. Attempts to salvage existing multi-nozzle sampling systems, or designing such systems for new installations, have the potential to create severe deficiencies from the perspective of representative sampling of particulate matter in accident conditions. With the obvious exception of instances where the contaminant is gaseous (tritium or noble gases) and gas mixing is complete, it is difficult to continue to defend the use of isokinetic, multi-nozzle sampling systems without demonstrating their compliance with this standard.

7 Quality assurance and quality control

The purposes of a Quality Assurance (QA) program are to provide assurance to facility management teams, regulatory agencies, and the public of the validity of air sampling data, and to identify any deficiencies in the sampling equipment and procedures so that corrective action can be taken. The tools used to accomplish these objectives include documentation, maintenance, inspection, and calibration.

7.1 Quality assurance plan

Every facility that conducts radiological air emissions sampling shall have a QA Program that

addresses the quality related activities of the air sampling program. A specific QA Plan may be developed and implemented. As the minimum, the QA Program shall address the quality aspects of the air sampling program in the following areas:

— organizational responsibilities;

— personnel qualifications;

— administrative controls;

— means for identification of sources;

— basis for the selection of sampling points. The methodology for verification of compliance with mixing requirements shall be documented;

— basis for selection of sampling and monitoring systems. The methodology for demonstrating compliance with performance requirements shall be documented;

— sample collection and tracking procedures;

— calibration methods and calibration standards;

— system operating procedures;

— maintenance and inspection procedures;

— procedure qualification;

— data quality objectives and how they are accomplished;

— audit and surveillance procedures;

— corrective action program;

— reporting and notification system;

— program documentation requirements;

— data analysis;

— inspection status and disposition of deficient items and conditions.

7.2 Documentation

Documentation is an integral part of any QA program. The recordkeeping system must ensure that all results are well documented and retrievable for analyses, audits, and archival purposes. The storage of data is as important as the collection of data. It should have an index arranged by storage files in a manner that will provide ready access. A copy of all documentation shall be maintained at a location remote from the principal data storage area.

Documents affecting the quality of air sampling data shall be prepared and reviewed by qualified personnel. The distribution of such documents shall be controlled.

A records system shall be established by the responsible organization that recognizes internal, external, and regulatory requirements. Such a records system shall designate records, their storage requirements, retention period, legibility requirements, identification and retrievability.

7.3 System characterization and documentation

The quality assurance program shall assure that the air sampling system and its components are characterized and documented.

7.3.1 Source term

Drawings of the ventilation system serving each monitored stack shall be maintained. Modifications to the system performed during construction or anytime thereafter shall be described in detail. This includes changes to the ventilation system or changes to processes that might effect the effluent. The nature of the processes serving each stack shall be identified, including information about the identity of the radionuclides as well as their chemical and physical forms. The air cleaning systems associated with each stack shall be identified as well as the probable nature of releases resulting from the possible failure of these systems.

7.3.2 Effluent flow characterization

The results of studies to characterize the flow conditions of the effluents shall be documented (e.g., spatial and temporal variations in flowrates across the stack or duct, checks for cyclonic flow, estimates of particle size distributions, etc.). The documentation shall include or list all procedures employed, times and dates of the measurements, individuals involved, equipment used, and any pertinent information regarding facility operations.

7.3.3 Design and construction

Documentation that describes the objectives of each stack sampling system, and includes or lists all radionuclides and their physical and chemical forms, shall be available. If a particular component is present but not sampled, the reasons should be discussed.

The rationale and any supporting evidence for sampling at a particular location along the duct or stack shall be documented. Similarly, the rationale for sampling at a particular point(s) within (across) the stack or duct shall be documented. Documentation that explains the rationale for the design of the sampling system shall be available. This includes documentation regarding the choice of the transport system, the material, diameter and configuration of the sampling lines, the choice of filters or absorbers, the selection of flowmeters, etc. Also, there should be a means for allowing verification that the installed sampling equipment is that described in the documentation. This can be accomplished by identification marks on the installed components. An evaluation of particulate losses in the sampling lines shall be documented. Other design documents that shall be maintained include engineering change control documents, equipment manuals and vendor supplied information.

7.4 Training

Individuals involved in system operation, inspection, audits, surveillances, and calibrations shall receive training in these commensurate with their nature. Training requirements shall be determined by the responsible management organization and documented.

7.5 Maintenance and inspection requirements

The requirements for maintenance and inspection depend upon the nature of the sampling equipment. Routine maintenance should be performed as described in the manufacturer's equipment manuals. Non-routine maintenance should also be performed as indicated by the results of inspections.

Inspection and maintenance activities shall be described in procedures. Checklists should be employed as part of inspection protocols, and, after use, a checklist should become a part record of the inspection. The inspection and maintenance records shall include the nature of the inspection or maintenance, reasons for the inspection or maintenance, names of the individuals involved, times and dates, identity of the equipment employed, and a description of any replacement parts or materials. All deficieces identified during scheduled and unscheduled inspections shall be dispositioned. A summary of recommended maintenance and inspection requirements is given in table 4.

Regularly scheduled inspections shall be performed at least once a year, possibly concurrent with calibrations. Ideally, the same individuals responsible for the calibrations should also be responsible for the inspections.

The inspections should include but not be limited to:

— checks of nozzle position and orientation;

— the measurements of the nozzle opening and checks for dust accumulation;

— functional checks of instrumentation;

— visual inspections for corrosion, physical damage or dust loading to the sampling lines and equipment;

— checks to ensure the tightness of all fittings and connections;

— leak tests.

7.5.1 Sampling system flowmeter inspections

Mass flowmeters should be checked at least quarterly with a secondary or transfer standard, where a transfer standard is typically a calibrated mass flowmeter placed in series with the unit to be tested. Unscheduled calibrations may be needed if any maintenance to the sampling system has been conducted that could affect the performance of the flowmeter. The flowrate at which the mass flowmeter is checked shall be at a level that is within $\pm 25\%$ of the nominal design sampling rate of the system. If the flowrate, q_{std}, of the flow meter being tested differs by more than 10% from the value indicated by a secondary standard, the flowmeter shall be removed from service for maintenance and calibration.

Flow through critical flow venturis should be checked at the start of each sampling period by observing the values of ΔP_m (differential pressure across the meter) and ΔP_f (differential pressure across the filter). If the value ΔP_m is less than that needed for critical flow, the vacuum system shall be checked to determine the cause. If the value of ΔP_f is less than 70% of that normally observed when the particular filter or collector is used, the critical flowmeter shall be inspected for blockage, or the sampling system shall be checked for other possible problems. The critical

Table 4 — Summary of maintenance, calibration and field check requirements.

Item	Frequency or Criterion	Section of Text where Referenced
Cleaning of thermal anemometer elements.	As required by application.	6.1.2.1
Inspect pitot tubes for contaminant deposits.	At least annually	6.1.2.2
Inspect pitot tube systems for leaks.	At least annually	6.1.2.2
Inspect sharp edged nozzles for damage.	At least annually or after maintenance that could cause damage	6.2.4.5
Check nozzles for alignment, presence of deposits, or other potentially degrading factors.	Annually	6.2.4.8
Check transport lines for need for cleaning HEPA filtered applications.	Annually	6.3.6
Clean transport lines	Visible deposits for HEPA filtered applications. Surface density of 1 g/cm^3 for other applications	6.3.6
Check mass flow meters of sampling systems with a secondary or transfer standard.	At least quarterly	7.5.1
Check sampling flow rate through critical flow venturis.	At the start of each sampling period	7.5.1
Inspect rotameters of sampling systems for presence of foreign matter	At the start of each sampling period	7.5.1
Check response of stack flow rate systems.	At least quarterly	7.5.2
Leak test aerosol transport system.	At least annually	7.5.3
Calibration of flow meters of sampling systems.	At least annually	7.6.1
Calibration of effluent flow measurement devices.	At least annually	7.6.2
Calibration of timing devices.	At least annually	7.6.3

1   flowmeter shall be removed from service for cleaning and re-calibration if it is the cause of the
2   erroneous reading. If the value of ΔP_f is greater than 130% of that normally observed, the filter or
3   collector should be inspected for possible problems.
4
5   Rotameters do not need to be checked in the field with secondary standards unless any mainten-
6   ance or changes have been made to the sampling system that could affect its accuracy. A rota-
7   meter should be inspected at the start of each sampling interval for assurance that no foreign
8   matter has been deposited on inside surfaces in the measurement tube. If foreign matter is visible,
9   the rotameter shall be removed from service, cleaned, and re-calibrated.
10

11   **7.5.2 Continuous effluent flow measurement apparatus**
12

13   On a quarterly basis, response checks should be made of the flowrate readings from in-stack
14   equipment through use of a reference Prandtl-type pitot-static tube. If a thermal anemometer or
15   pitot tube is used in the stack or duct, the reference pitot tube should be placed in the vicinity of
16   the in-stack device at a point where, based on previous measurements (e.g., EPA Method 2
17   measurements on an EPA Method 1 grid [40 CFR 60, Appendix A]), the velocity reading is either
18   the same as that of the in-stack device or a known correction factor can be applied to provide a
19   ratio of the two velocity readings. If the in-stack sensor is a pitot tube, the velocities calculated
20   from use of the two tubes should be within ±10% (after taking into account any correction
21   factors). If the in-stack sensor is a thermal anemometer, the velocity determined from use of the
22   reference pitot tube, V, should be converted to the equivalent velocity at standard conditions, V_{std},
23   through use of:
24

$$V_{std} = V\frac{T_{std}}{T}\frac{p}{p_{std}} \qquad\qquad (10)$$

25

26   For the performance of the thermal anemometer to be acceptable, the ratio the velocity at standard
27   conditions indicated by the in-stack sensor and the reference sensor should be within ±10%.
28

29   If the velocity value from either an in-stack pitot tube or thermal anemometer is outside of the
30   specified range, the cause of the difference must be determined. The device may need to be
31   recalibrated. Also, if a sensor requires maintenance that could affect the calibration, the device
32   must be recalibrated.
33

34   If the flow sensor is a pitot tube, response checks shall be made at least quarterly to verify the
35   functionality of any pressure gauges used in conjunction with the pitot tube readout. This check
36   may be a simple test to show the application of a pressure differential causes an appropriate output
37   of the gauge.
38

39   If an acoustic flowmeter is used as the in-stack equipment, at least quarterly performance checks
40   should be made by comparing the average velocity determined with the acoustic flowmeter to the
41   velocity at a reference point determined with a Prandtl-type pitot-static tube. Based on EPA
42   Method 2 measurements taken during calibration of the acoustic flowmeter, a ratio can be estab-
43   lished between the average velocity and the velocity at the selected reference point. The velocity
44   measured with the acoustic flow meter should agree within ±10% of the single point pitot tube
45   measurement when the latter is corrected with the velocity ratio. If this criterion is not met,
46   necessary evaluation, repair, maintenance, and calibration procedures should be used to solve any
47   problems.
48
49

7.5.3 Leak tests

A leak test of the transport system involves sealing the nozzle opening with a tight fitting cap or covering it with a short section of plastic tubing sealed at one end. At its simplest, the leak test is a check that the indicated flow has fallen to zero. A more elaborate test involves measuring the static pressure in the lines with a U-tube manometer (or similar device). After sealing the nozzle, a vacuum is generated that is the order of 4 kPa (15" H_2O). The sampling line is shutoff just upstream of the pump, and the vacuum in the transport system is recorded. After one minute, the pressure is measured again. A loss of 0.1 kPa (0.5" H_2O) or more indicates a leak.

7.6 Calibration

Measurement and test equipment shall be calibrated using standards whose calibration is traceable to NIST (or other nationally recognized standards) or derived from accepted values of natural physical constants. The principal calibration activities on a sampling system involve the verification of sample flowrate, sampling time, and effluent flowrate. The suggested calibration frequency is annually for systems operated under normal or controlled environmental conditions. For systems used under extreme conditions, the calibrations should be conducted more frequently, e.g., every six months.

The methods used in calibrating all equipment and systems shall be clearly described in procedures. The results of all calibrations shall be recorded. This includes flowmeter and timer calibrations. The records shall include the names of the individuals involved, times and dates, and the types and serial numbers of the calibration equipment.

7.6.1 Calibration of sampling system flowmeters

The goal of the flowmeter calibration is to help ensure that the uncertainty in the measurement of the total volume of air sampled is ≤10%. Annex E describes a number of considerations for uncertainty analysis. All flowmeters shall be calibrated at least annually against devices that are either based on first principles (bubble meters or proof meters) or that are traceable to NIST.

The internal sensing region of a flowmeter shall be inspected before calibration. If there is any indication of surface deposits, the internal components of the flowmeter shall be cleaned or replaced.

Mass flowmeters should be calibrated at conditions corresponding to 40%, 70%, 100%, 130% and 170% of the nominal flowrate in terms of standard conditions. Other values may be used; however, technical justification must be documented to show that the use of the selected points will provide calibration data equivalent to, or superior to, the recommended points. If the flowrate through the sampling system could, under normal conditions or anticipated or accident conditions, exceed the limits recommended herein for flow calibration, additional calibration points shall be used to encompass the possible operating range.

Critical venturi flowmeters need only to be calibrated at a single point that corresponds to operating conditions with a sufficient pressure differential across the meter such that the velocity is sonic. The temperature at the entrance of the critical flowmeter during calibration should be within ±5°C of the average temperature anticipated at that same location during sampling. The absolute pressure at the entrance of the critical flow meter should be within ±2% of the average absolute pressure anticipated at that location.

Rotameters shall be calibrated at flowrate conditions that correspond to the average anticipated flowrate during sampling, and at 75% and 125% of the anticipated sampling flowrate.

The following approach, described in U.S. Nuclear Regulatory Commission (NRC) Guide 8.25 (US NRC 1992) can be employed to calculate the total uncertainty in the volume of air (E_{QT}):

$$E_{QT} = \left(F_k \, E_s\right)^2 + E_c^2 + E_t^2 \tag{11}$$

where: E_s is the error (dimensionless) in reading the flowmeter scale. This can be estimated by dividing one-half the value of the smallest scale division by the indicated flowrate.

F_k is a fluctuation constant. This is set at 1 for a meter whose readings do not fluctuate. If there are fluctuations, the parameter is set taken to be the average number of scale unit above and below the mean indicated value.

E_c is error (dimensionless) associated with determining the calibration factor, i.e., correcting the indicated flow. As an approximation, the error associated with the calibration instrument may be used.

E_t is error (dimensionless) associated with the measurement of the sampling time.

7.6.2 Calibration of effluent flow measurement devices

An effluent flow measurement system must be calibrated at least annually against a reference method. The Reference Method for this standard is a modification of EPA Methods 1 and 2, which is discussed together with the requirements for the calibration in annex A. The goal of the calibration is to measure flowrate with an accuracy relative to the Reference Method that is within ±10%.

7.6.3 Calibration of timing devices

Timing devices should be calibrated at least annually. The maximum acceptable error is 1 minute per month.

7.7 System performance criteria

Assuring satisfactory sampling system performance requires the implementation of carefully planned design, inspection, and maintenance procedures. Throughout this document, performance criteria for various elements have been included in the discussion of each element. For convenience, they are summarized in table 5. These criteria cover aspects of system design, operation, maintenance and calibration.

7.8 Technical guidance

QA programs are typically prepared in response to specific guidance documents. QA guidance may be obtained from documents such as 40 CFR 61, EPA/600/4-77/027b, 1988; EPA/520/1-80-012, 1980; U.S. DOE Order 5700.6C, Order 5400.2A, Order 5484.1, Order 5480.4, Order 5400.5; U.S. NRC Regulatory Guide 4.15; ASME NQA-1, 1990; and Methods of Air Sampling and Analysis, General Techniques, Part 26.

Table 5 — Summary of performance criteria. Table is based on presence of aerosol particles in the stack or duct. If no particles can be emitted, criteria are to be based on gas characteristics only.

Performance criterion	Reference
Total transport of 10 μm AD particles and vaporous contaminants shall be >50% from the free stream to the collector/analyzer.	Clauses 6.3.1 and 6.4
Sampler nozzle inlet shall have a transmission ratio between 80% and 130% for 10 μm AD particles.	Clause 6.2.2
Sampler nozzle shall have an aspiration ratio that does not exceed 150% for 10 μm AD particles.	Clause 6.2.2
Characteristics of a suitable sampling location are: a) coefficients of variation over the central 2/3 area of the cross section within ±20% for 10 μm AD particles, gaseous tracer, and gas velocity. b) flow angle <20° relative to the long axis of the stack and nozzle inlet. c) the tracer gas concentration shall not vary from the mean >30% at any point on a 40 CFR 60 Appendix A Method 1 velocity mapping grid.	Clause 5.2.2.2
Effluent flowrate monitoring required if flow variation is > ±20% in a year.	Clause 6.1.1
Effluent and sample flowrate shall be measured within ±10%.	Clauses 6.1.1 and 7.6.1
Continuous sample flowrate monitoring and control required if flow varies > ±20% during a sample interval. Flow control shall be within ±15%.	Clauses 6.7.2 and 6.7.3
PIC 1: Continuous measurement of effluent flowrate and continuous measurement and control of sampling flowrate (to track flowrate in stack or duct within ±20% of a predetermined value).	Clauses 6.1.1, 6.7.1 and 6.7.3
PIC 2: Continuous flowrate monitoring unless flowrate variation is less than ±20% during a year	Clause 6.1.1
Periodic inspections of nozzles, transport lines, sample and effluent flowmeters, shall be conducted.	Clause 7.5
Periodic calibrations of effluent and sample flowmeters, CAMs, and sample analysis instrumentation shall be conducted.	Clause 7.6

Annex A
(informative)

Techniques for measurement of flowrate through a stack or duct

A.1 Introduction

The volumetric flowrate, q, through a stack or duct is defined as:

$$q = \int_{Area} V dA \qquad \text{(A-1)}$$

where: V is the velocity at any location across a stack or duct;

        A is the cross sectional area of the duct.

ANSI and the American Society of Mechanical Engineers (ANSI/ASME PTC-38, 1980) standardized a method for determining q, which involved measuring the velocity at a finite number of points in a duct, where each point was chosen as the center of an area element. They utilized the relationship:

$$q = \sum_{i=1}^{N} V_i \Delta A_i \qquad \text{(A-2)}$$

where: V_i is the velocity at the midpoint of the ith element;

        ΔA_i is the area of the ith element.

The cross section of the stack or duct is divided into N elements. In usual practice, all of the N elements have equal areas. The ANSI/ASME approach was embodied in EPA Methods 1 and 2 (40 CFR 60, Appendix A), which serves as the Reference Method for this ANSI Standard (clause 6.1.1). The requirements for absence of cyclonic flow given in Methods 1 and 2 are also included in the Reference Method.

The flowrate q is associated with the air density, ρ, that exists in the stack or duct. Density, is calculated from the ideal gas equation for dry air, viz:

$$\rho = \frac{p}{RT} \qquad \text{(A-3)}$$

where: p is the absolute pressure in the stack or duct (kPa);

        T is the absolute temperature (K);

        R is the gas constant for air (0.287 kJ/kg × K).

The flowrate at standard conditions, q_{std}, is the parameter that is to be calculated for reporting and analysis purposes, and it is related to the actual flowrate, q, by:

$$\rho q = \rho_{std} q_{std} \tag{A-4}$$

where: ρ_{std} is the density of air based on standard temperature and pressure (101.3 kPa and 298 K).

The flowrate at standard conditions can then be expressed from equation (A-4) as:

$$q_{std} = q \frac{T_{std}}{T} \frac{p}{p_{std}} \tag{A-5}$$

In practice, q is determined from velocity measurements at traverse points specified in EPA Method 2, with the value calculated from equation (A-2). The temperature and pressure in the stack or duct are measured in accordance with the requirements of EPA Method 2.

A.2 Special considerations for use of EPA methods 1 and 2 in sampling stacks and ducts of the nuclear industry

The Reference Method for determining air flowrate through a stack or duct, modified EPA Methods 1 and 2 (40 CFR 60, Appendix A), was developed for flowrate determinations in non-nuclear stacks and ducts. There are several differences with typical sampling in nuclear stacks and ducts that need to be taken into consideration.

A.2.1 Pitot tubes

An S-type pitot tube is recommended under EPA Method 1, for the purpose of reducing the risk of dust plugging the ports of the pitot tube when measurements are made in dusty environments. Dust loading during velocity mapping in a stack or duct in the nuclear industry is not usually a concern, thus Prandtl-type pitotstatic tubes should be considered as the reference apparatus for sampling under the requirements of the present standard. If there are situations where dust loading may be of concern, an S-type pitot tube should be considered.

A.2.2 Mean molar mass of the stack gas

Often in the industrial applications for which EPA Methods 1 and 2 were designed, the gas being tested contains products of combustion or elevated water vapor resulting from drying operations. In contrast, the gas in most stacks and ducts of the nuclear industry is ventilation air. It is unnecessary to determine the mean molar mass, M (called the molecular weight in EPA Method 2), for most stacks and ducts. However, if it can be anticipated that there will be more than 10% water vapor in the stack or duct, or if there are other gases that will change the mean molar mass by more than 4% from the value for dry air (28.96 kJ/kmol) a determination is made of the mean molar mass of the gas following the method recommendations given in EPA Method 2 (Section 2.6).

1   If it is necessary to measure the mean molar mass, the resulting value is used to calculate the gas
2   constant in equation (A.4) as:

3

$$R = \frac{R_u}{M} \tag{A-6}$$

4

5   where: R_u is the universal gas constant (8.314 kJ/kmol × K).

6

7   **A.2.3 Thermal anemometers**

8

9   If the mean molar mass and water content of the stack gas are in accordance with the values
10   stated, the gas can be treated as air; if the dust loading in the stack or duct is such that any
11   deposits on a thermal anemometer probe will not change the calibration of a thermal anemometer
12   by more than 3% during the course of the velocity measurements; and, if there is no condensation
13   of water vapor or other vapors on the sensor during flow measurements, a thermal anemometer can
14   be used in this ANSI Standard in lieu of a pitot tube.

15

16   When a thermal anemometer is used for velocity mapping in a stack or duct, the flowrate based on
17   standard conditions, q_{std}, is determined from:

18

$$q_{std} = \sum_{i=1}^{n} V_{std,i}\, \Delta A_i \tag{A-7}$$

19

20   where: $V_{std,i}$ is the equivalent velocity at standard conditions measured with a properly calibrated
21   thermal anemometer at the center of the ith element of area.

22

23

24   **A.3 Conversion of data from single point or single line measurements to total flowrate**

25

26   If continuous single point velocity measurements from a pitot tube or a thermal anemometer, or line
27   integral measurements from an acoustic flow meter are used to infer the total flowrate through a
28   stack as a function of time, the resulting data must include a correction factor account for the
29   shape of the velocity profile. The correction factor is determined by comparing flowrate determina-
30   tions from use of the single point technique with those of the Reference Method for this Standard
31   (EPA Methods 1 and 2).

32

33   **A.3.1 Pitot tube**

34

35   The velocity-averaging correction factor for a pitot tube, C_{pt}, is defined as:

36

$$C_{pt} = \frac{VA}{q} \tag{A-8}$$

37

where: V is the velocity measured by a pitot tube at the single point where monitoring will be carried out;

A is the cross sectional area of the duct;

q is the flowrate through the stack or duct as determined from use of the Reference Method and as calculated from equation (A-2).

Usually, the single point would be located near the center of the duct. Multiple points could be used, in which case the value of V is the average of the values from the multiple points.

The velocity, V, will be continuously monitored during the period that the Reference Method testing is performed to established the velocity-averaging correction factor, C_{pt}. If the value of V were to change by more than 5% during the course of testing, the data should be rejected and the test repeated. If the stack is subject to long-term flowrate variations that exceed ±25%, additional tests should be carried out at the highest flowrate (if it exceeds the base condition by more than 25%) and the lowest operational flowrate (if it deviates from the base condition by more than 25%) to establish values of the velocity-averaging correction factor at those conditions. A single value of the flow correction factor may be used if the range of flow correction factor values is within ±7% of the base condition. If the values of the correction factor at the extremal flow conditions are greater than ±7% of the base condition, then a relationship must be established between the velocity correction factor and flowrate.

At least two replicate tests should be employed to establish a value of the correction factor. During routine use, the flowrate is determined from readings of the single point pitot tube using:

$$q = C_{pt}VA \tag{A-9}$$

A.3.2 Thermal anemometer

A thermal anemometer located at a single point in a flow field will provide a reading that is related to the total flowrate at standard conditions through the relationship:

$$q_{std} = C_{ta}V_{std}A \tag{A-10}$$

The value of the velocity-averaging correction factor, C_{ta}, is determined by comparing the readings of a thermal anemometer operated at a single point with simultaneous data from a Reference Method flowrate test. The data from the Reference Method test must be corrected to standard conditions through use of equation (A-5). Requirements for carrying out tests are the same as those for the pitot tube correction factor, clause A.3.1.

Continuous measurements of the effluent flowrate at standard conditions can be obtained by using a rake of thermal anemometers, with the individual anemometer elements placed on an EPA Method 1 grid. Provided the electronic signals are processed properly, the output reading of such a system will be the flowrate according to equation (A-6).

A.3.3 Acoustic flow meter

The reading provided by an acoustic flow meter is a distance-weighted average velocity across a line between a sending transducer and a receiving transducer. As such, the velocity reading is not directly related to flowrate even along the line because flowrate must be based on an area-weighted average velocity. To obtain the flowrate through a stack or duct from acoustic flow meter readings also requires development of a velocity-averaging correction factor, C_{af}, which will give:

$$q = C_{af} V A \qquad \text{(A-11)}$$

where: V is the line average velocity obtained from the acoustic flow meter.

The approach and requirements for determining C_{af} are the same as those for the single point pitot tube.

A.3.3 Small stacks and ducts

The flowrate through small stacks and ducts (those with internal diameters, or hydraulic diameters, that are less than 105 mm) could be monitored with a single point provided the appropriate flow correction factor is employed. The Reference Method for determining the actual flow in the duct is that given by EPA Methods 1a and 2a (40 CFR 60, Appendix A), or other techniques that would provide equal or better accuracy.

Annex B
(informative)

Modeling of particle losses in transport systems

Aerosol particles can be deposited on internal surfaces of transport systems as a result of the actions of mechanisms that cause particles to move transverse to air flow streamlines. Included are such phenomena as gravitational settling, inertial impaction, turbulent inertial deposition, and Brownian diffusion. For most transport systems, the Brownian diffusion mechanism is of significance only for aerosol particles with sizes smaller than approximately 0.3 μm; whereas, the other mechanisms are of importance for particles larger than this size. Turbulent deposition is of consequence for flows with Reynolds numbers (Re) >2200, where the Reynolds number is given by:

$$Re = \frac{\rho U_m d_t}{\mu} \qquad (B-1)$$

where: ρ is gas density (kg/m^3);

   U_m is mean (spatial) velocity at a cross section of the transport system (m/s);

   d_t is tube diameter (m);

   μ is air dynamic viscosity (Pa $\bullet$ s).

For a tube of circular cross section, the Reynolds number can also be expressed as:

$$Re = \frac{4\rho q}{\pi d_t \mu} \qquad (B-2)$$

where: q is volumetric flowrate through the tube (m^3/s) and is equal to the product of the mean velocity and the cross sectional area.

The combination of flowrate and tube diameter of most aerosol sampling systems is such that the flow is turbulent.

Empirical or semi-empirical models for predicting the effects of the various depositional mechanisms exist for most components of a sampling system. For nozzles, the losses are controlled by inertial forces including those associated with flow turbulence, the Saffman force and, occasionally by gravitational settling; for vertical tubes, the depositional losses are assumed to be controlled by turbulent and Brownian diffusion; for horizontal tubes, the losses are caused by gravitational settling, turbulent inertial deposition and Brownian diffusion; and, for bends, the losses are controlled through the effects of inertial impaction. The data bases used for generating the models typically assume the velocity and concentration profiles are uniform at the entrance section of the component of interest. It is to be expected that this assumption would not be fulfilled in many sampling systems because the flow disturbance created by an upstream component could affect the

1 depositional characteristics of a succeeding component; however, in experimental studies with a
2 composite transport system (nozzle, horizontal tube, inclined tube, vertical tube and bends)
3 McFarland et al. (1991) and Wong (1992) showed that the use of a model that was based on a
4 sequential combination of components with assumed undisturbed inlet conditions, compared well
5 with experimental data.
6
7
8 ## B.1 Aerosol penetration through transport system components
9
10 The penetration, P_j, of aerosol through the jth component of a transport system is defined as:
11

$$P_j = \frac{c_{e,j}}{c_{i,j}} \qquad \text{(B-3)}$$

12
13 where: $c_{e,j}$ is aerosol concentration at the exit plane of a component;
14
15        $c_{i,j}$ is aerosol concentration at the inlet plane of a component.
16
17 If there are n components in a sampling system, it is assumed the overall penetration, P, can be
18 calculated as though each component were independent, which gives:
19

$$P = \prod_{j=1}^{n} P_j \qquad \text{(B-4)}$$

20
21 Estimates of particle losses in sampling systems can often be adequately performed by hand
22 calculation (Brockman 1993) or with the aid of available software. As an example, the U.S. Nuclear
23 Regulatory Commission has made available PC-based software, DEPOSITION, for calculating the
24 losses of aerosol particles in transport systems (Anand and McFarland 1993). It includes models for
25 losses in certain types of nozzles, straight tubes and bends; however, losses associated with tube
26 fittings that serve as transitions in tube diameter, either to enlarge or reduce the diameter, are not
27 currently taken into account. Until such data are available, the experimental results of Williamson
28 et al. (1987) may be used as a guide for enlargement fittings; however, it is anticipated that when
29 additional data or models are developed, the results may show that an expansion with a 90° half
30 angle will provide satisfactory performance. Williamson et al. (1987) conducted a study on the
31 effect of geometry on the losses in specially-designed isokinetic sampling nozzles, where the nozzle
32 inlets were smaller in diameter than the connecting flow tubing. Depositional losses were minimized
33 when the half angle between inlet diameter of the nozzle and the transport tube was from 7° to
34 14° (figure B.1). For fittings that involve a reduction in area from a larger diameter to a smaller
35 diameter, the work of Loo and Cork (1988) shows that the angle can be rather substantial. They
36 recommended a half angle of 40° to 50° for the transition from a larger diameter to a smaller
37 diameter tube (figure B.2), which in their case was from a 28 mm diameter tube to a 3 mm nozzle
38 in a virtual impactor. This transition, in a vertical orientation, accommodated the transmission of
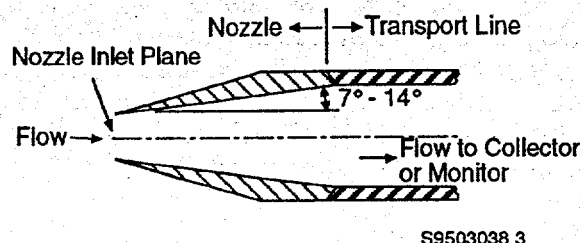39 20 μm AD particles.

S9503038.3

Figure B.1 — The half angle of an expansion in an aerosol transport system could be set between 7° and 14° based on results of Williamson et al. (1987)
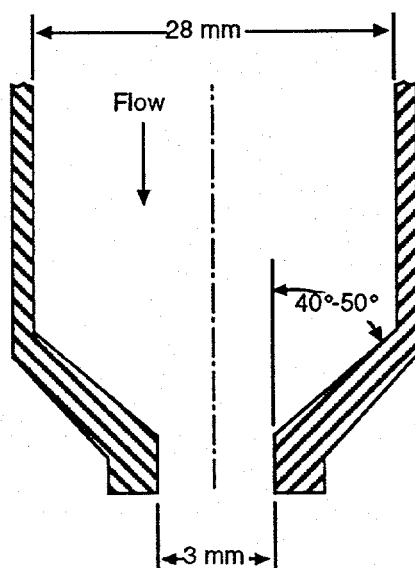

S9503038.4

Figure B.2 — The angle for transition from a larger to a smaller tube could be set between 40° and 50° based on results of Loo and Cork (1988)

B.1.1 Wall losses in nozzles

At the present time there is no general model for predicting wall losses in nozzles. Fan et al. (1992) made an experimental correlation of wall losses as a function of design and operational conditions for isokinetic nozzles of a Willeke-Okazaki configuration (1987), where those nozzles are similar to the ANSI N13.1-1969 design but with the exception there is no bend. The model of Fan et al. (1992) is based on experiments, which encompassed sizes of 10 and 20 μm, so it cannot be used as a general predictive tool for all nozzle applications; nevertheless, it does provide the basis for estimating internal wall losses in the straight region of ANSI N13.1-1969 nozzles upstream of the bends.

The code, DEPOSITION 2.0, includes the Fan et al. (1992) model for use with isokinetic nozzles. It may overestimate the losses in more modern designs of isokinetic nozzles such as is illustrated in

65

figure B.3 (Chandra 1992). A shrouded nozzle (McFarland et al. 1989) is basically a nozzle fitted with a flow decelerator (see figure 2 of this Standard). It has lower wall losses than an unshrouded nozzle and it is less susceptible to off-design sampling conditions (e.g., off-angle flow direction, changes in sampling flowrate or changes in free stream velocity) than an unshrouded nozzle; (Chandra and McFarland 1995). If the DEPOSITION model is applied to a system fitted with a shrouded nozzle, the nozzle size and velocity should be those associated with conditions for the inner nozzle in the shroud (velocity in the shroud and diameter of the actual nozzle). It is to be anticipated that more extensive models will be developed for characterizing losses in shrouded nozzles, which will then be incorporated into predictive codes (e.g., DEPOSITION 3.0 or higher).

B.1.2 Straight tubes

The penetration of particles through a straight tube is calculated from:

$$P = \exp\left[-\frac{\pi d_t v_e L}{q}\right] \tag{B-5}$$

where: v_e is effective depositional velocity;

L is length of the straight section of tubing.

The effective depositional velocity is the vector sum of the gravitational settling terminal velocity (which is always directed downward), and the turbulent inertial deposition and Brownian diffusion velocities which are directed radially outward in a tube. A basic assumption when using this model is that aerosol particles are well mixed across any cross section of a tube.

The effective deposition velocity for an inclined tube, figure B.4, was modeled by Anand et al. (1992) as:

$$v_e = \frac{1}{2\pi}\int_0^{2\pi}(v_d - v_{ge}\sin\alpha)\,d\alpha \tag{B-6}$$

where: α is angular coordinate of a tube cross section (figure B.4);

v_d is depositional velocity due to the combined effects of thermal (Brownian) diffusion and turbulent inertial deposition;

v_{ge} is cross-stream component of gravitational settling velocity.

For a tube that is inclined at an angle of ϕ relative to the vertical direction:

$$v_{ge} = v_g \sin\phi \tag{B-7}$$

66

Nozzle ←|→ Transport Line

2.5 %

5 %

Flow → 7.7 mm

25 mm
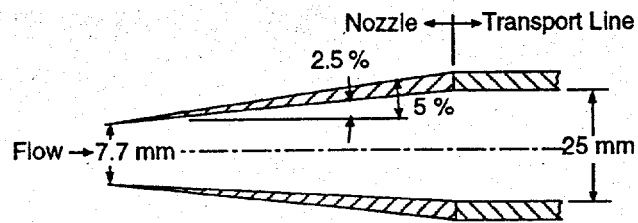
S9503038.2

Figure B.3 — Unshrouded nozzle of Chandra (1992), which has about 1/2 the wall losses of 10 μm AD aerosol particles than an ANSI 13.1 (1969) nozzle

FLOW

D

A

A

$\vec{V}_d$

α

Particle

$\vec{V}_g$

g

①

Section A-A
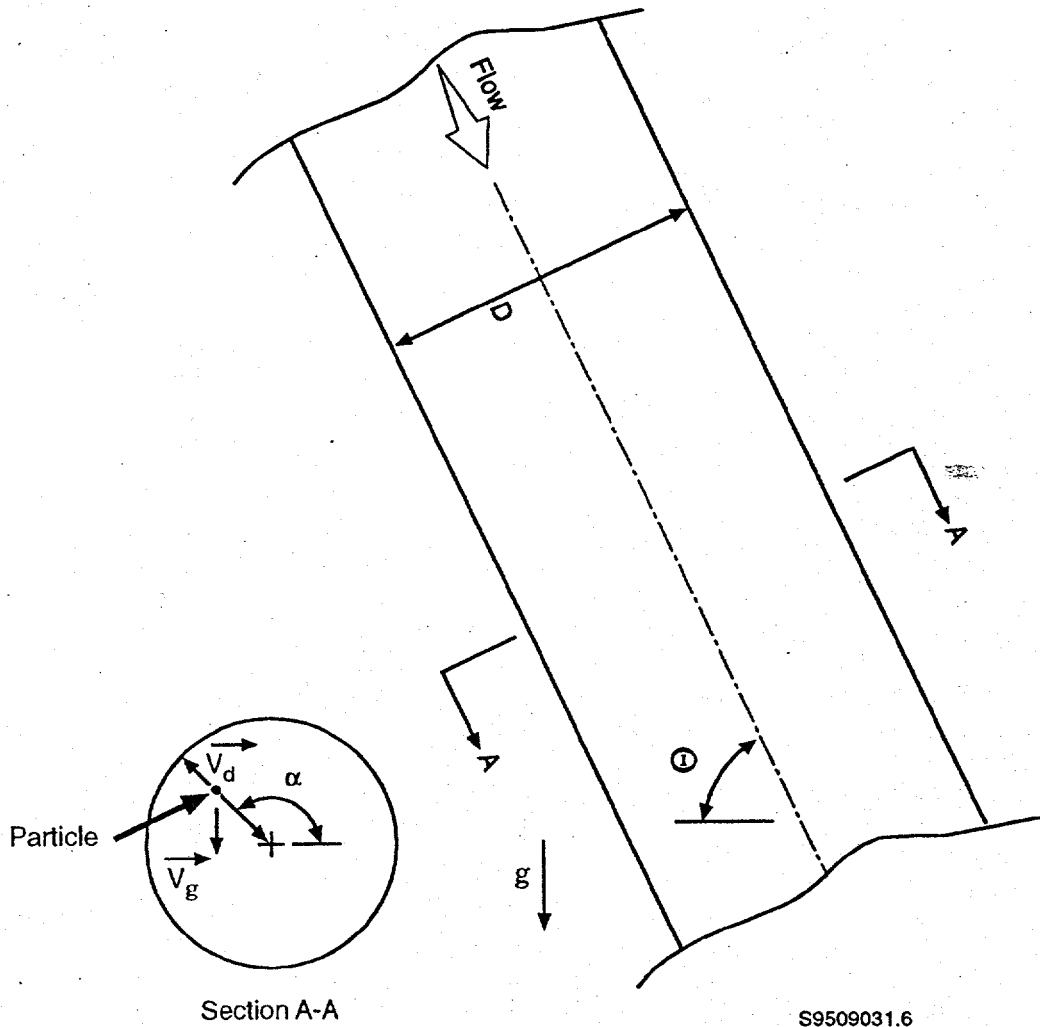
S9509031.6

Figure B.4 — Geometric model to illustrate parameters used to model aerosol deposition in a straight tube

1   where: v_g is the sedimentation velocity. Equation (B-6) is subject to a constraint, namely:
2

$$(v_d - v_{ge}\sin\alpha) > 0 \qquad \text{(B-8)}$$

3
4   If the constraint is not satisfied:
5

$$v_e = 0 \qquad \text{(B-9)}$$

6
7   The constraint is necessary because otherwise the prediction would be equivalent to aerosol
8   particles being transported from the environment through the top (relative to the earth's surface) of
9   a tube.
10
11 If the effects of both gravitational settling velocity in the cross stream direction and the turbulent
12 inertial deposition velocity are of consequence, there will be a tube diameter that optimizes aerosol
13 penetration because for a fixed flowrate, tube sizes smaller than the optimal value will have
14 increased turbulent depositional losses and tube sizes larger than the optimum will have enhanced
15 gravitational depositional losses.
16
17 A dimensionless particle deposition velocity in tubes can be correlated with a dimensionless particle
18 relaxation time. Several semi-analytical models that lead to this correlation have been proposed;
19 however, at this time, none can predict deposition of particles in the inertial size regime
20 (>1 μm AD) from basic principles. Onda (1977) reviewed the various models and compared them
21 with experimental data and concluded the model of Beal (1970) provided the best fit. The present
22 version of DEPOSITION uses this model to predict the deposition. However, pure curve fitting of
23 experimental data could also be used to provide estimates of the depositional velocities. The latter
24 approach was used by Agarwal (1975), but his model does not take into account deposition due to
25 the Brownian diffusion mechanism.
26
27 Particle deposition in fully developed laminar flow can be modeled with the theory of Thomas
28 (1958) for gravitational settling and Gormley and Kennedy (1949) for Brownian diffusion. However,
29 true laminar flow does not often occur in straight tubes because straight tubing sections are usually
30 proceeded by disturbances such as bends. Typical sample transport tubes will have Reynolds
31 numbers that are >1000, which can cause the effects of any upstream flow disturbances to cause
32 flow mixing downstream from the disturbance and thus would render a well-mixed deposition model
33 such as equation (B-5) more relevant than a laminar model with no bulk fluid mixing. For this
34 reason, a well-mixed submodel, such as is utilized in DEPOSITION, can employed for straight tubes
35 when the Reynolds number is greater than 1000. For bends, a distinction is made between laminar
36 and turbulent flows.
37
38 **B.1.3 Bends**
39
40 Particle losses in bends are principally due to the effects of particle inertia—the air flow follows a
41 curved path and the particles tend to go straight. Neglecting Brownian diffusion, turbulent inertial

68

deposition, and gravitational effects, analyses show that for two-dimensional channels, the penetration is a function of the Stokes number, Stk, where:

$$Stk = \frac{C\rho_w D_a^2 U_m}{9\,\mu\,d_t}$$
(B-10)

where: C is Cunningham's slip correction (Fuchs 1964);

ρ_w is density of water;

D_a is aerodynamic particle diameter.

The analysis for particle deposition in bends of circular cross section is complicated by the fact the flow is three dimensional. A secondary flow is established as the air passes through the bend, where the secondary flow consists of a set of counter-rotating vortices in which air goes from the inside of the bend to the outside of the bend along the tube diameter, and goes in the reverse direction along the tube circumference. In this case, the particle deposition is a function of not only the Stokes number, but also the curvature ratio, R_o, and the Dean number, De, where:

$$R_o = \frac{R_c}{d_t}$$
(B-11)

and

$$De = \frac{Re}{\sqrt{R_o}}$$
(B-12)

where: R_c is the radius of the tube bend.

Pui et al. (1987) noted that for turbulent flow, when the curvature of the bend is such that $2.5 \leq R_o \leq 15$, the radius of curvature has little effect on particle trajectories and the deposition will depend, at most, on Stk and Re. Experimental data for the 90° bends with turbulent flow Reynolds numbers of 6,000 and 10,000 show that the penetration can be correlated with only the Stokes number, namely:

$$P = 10^{-0.963 Stk}$$
(B-13)

For laminar flow, Tsai and Pui (1990) numerically modeled particle deposition in 90° bends and their results include the effects of secondary flow. They carried out calculations over a range of curvature ratios and Dean numbers and provided empirical correlations of the results, which showed the efficiency depends upon the Stokes number, curvature ratio and the Dean number.
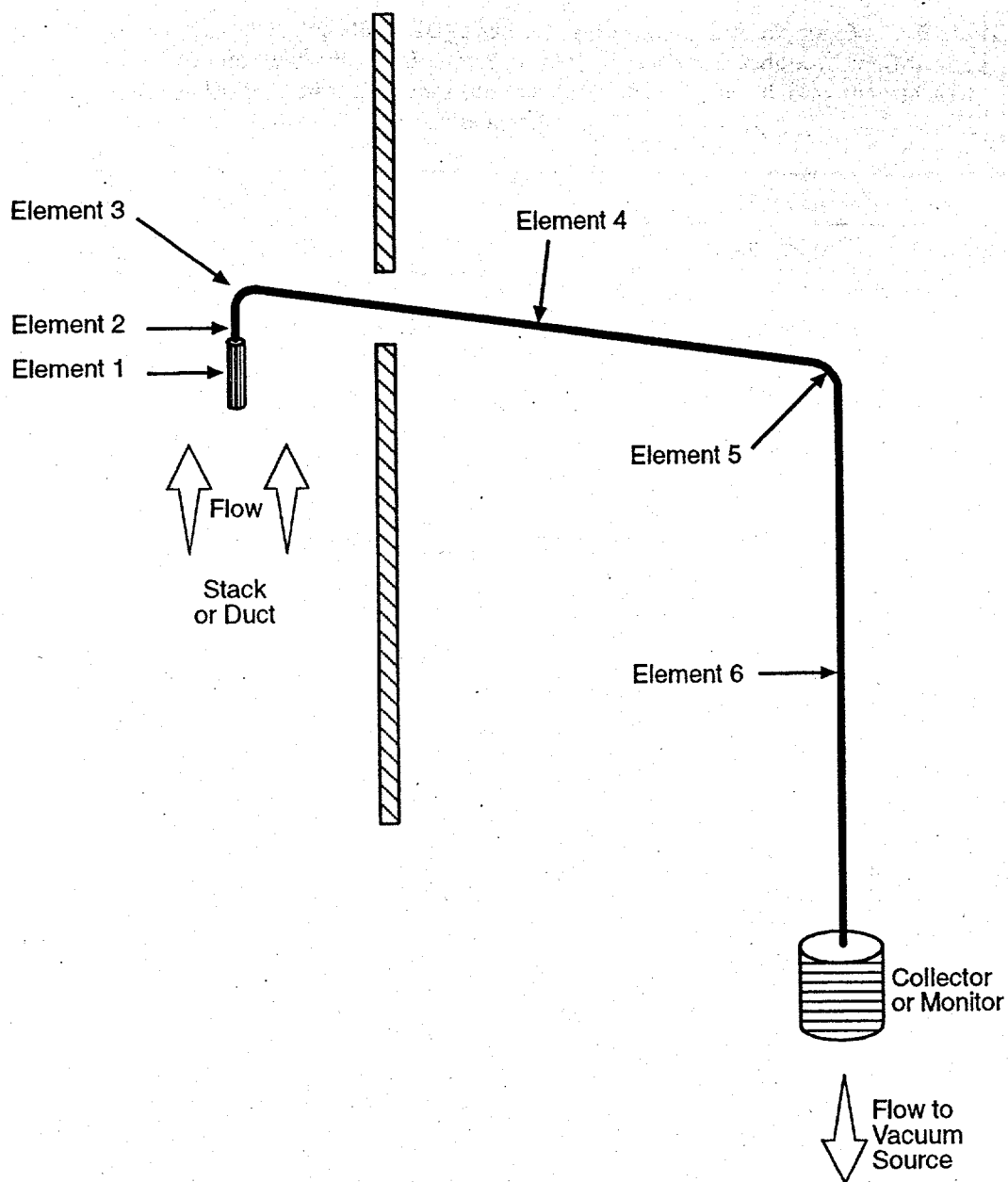
In the software DEPOSITION, the model of Tsai and Pui (1990) is used for Reynolds numbers <1100 and the model of Pui et al. is used for Reynolds numbers ≥1100.

B.2 Sample calculation of losses in a transport system

As an illustration of the calculation of particle losses in a transport system, assume the geometrical configuration shown in figure B.5 for a system that is designed to sample 10 μm AD aerosol particles at a flowrate of 56.6 liter/min (2 cfm) from a free stream that has a velocity of 20 m/s. Suppose the nozzle is a shrouded nozzle in which the velocity inside of the shroud is 6 m/s and the internal nozzle samples isokinetically from the 6 m/s stream. Also, assume the sampling tube has a 15.75 mm inside diameter (3/4-inch outside diameter with a 0.065-inch thick wall). The input and output values for the DEPOSITION 2.0 code are shown in table B.1.

The overall penetration through the system is 30.7%, with the losses being dominated by the bends. Were the optimal tube diameter that maximizes penetration (34 mm) to be used, the overall penetration would be 67.0%. The value of 30.7% associated with the 15.75 mm diameter tube would be unacceptable under the criterion given in clause 6.31; however, the performance of the 34 mm diameter tube would be acceptable.

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Figure B.5 — Layout of example aerosol transport system. Free stream velocity = 20 m/s and is reduced to 6 m/s in the shroud. Tube diameter is 15.75 mm, which is considerably smaller than the optimal diameter of 34 mm.

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Table B.1 — Example of using a computer code (DEPOSITION 2.0) to predict aerosol penetration through a transport system (figure B.5). Tube diameter is 15.75 mm, free stream velocity is 20 m/s with a shroud reducing that to 6 m/s at the inner nozzle inlet, and the particle size is 10 μm AD.

Input parameters	Output values
1) Flowrate: 56.6 liter/min	1) Penetration through nozzle (Element 1): 92.3%
2) Tube diameter: 15.75 mm	2) Penetration through Element 2: 98.5%
3) Number of components: 6 (including a shrouded nozzle which is the first element).	3) Penetration through Element 3: 66.0%
4) Particle density: 1 g/cm³	4) Penetration through Element 4: 85.7%
5) Particle size: 10 μm AD, monodisperse	5) Penetration through Element 5: 66.0%
6) Flowrate: 56.6 liter/min	6) Penetration through Element 6: 90.7%
7) Pseudo free stream velocity: 6 m/s	7) OVERALL PENETRATION: 30.7%
8) Element 1: Nozzle operated isokinetically in the shroud with an angle between free stream and inlet = 0°	
9) Element 2: Tube, 0.2 m long, 0° from horizontal	
10) Element 3: Bend, 90°	
11) Element 4: Tube, 2 m long, 0° from horizontal	
12) Element 5: Bend, 90°	
13) Element 6, Tube, 2 m long, 90° from horizontal	

Annex C
(informative)

Special considerations for the extraction, transport and sampling of radioiodine

C.1 General considerations

Obtaining samples of airborne radioiodine is complicated because it is present in air effluents in several forms, viz: as particulate matter, as elemental iodine (I_2), as hypoiodous acid (HOI) and in organic form, principally methyl iodide (CH_3I). The existence of the HOI form is not universally accepted, but it is postulated to be that otherwise indeterminate form with a depositing velocity lower than that of elemental iodine and that will penetrate a cadmium iodide bed but that will be collected by an iodophenol bed in a species sampler.

These chemical forms of radioiodine, particularly the elemental form, may be expected to initially deposit in ducts and in sampling lines and then subsequently be resuspended and emitted as the same or another form (Cline 1991). The organic form is the least depositing and only a small fraction of it is collected by some of the solid adsorbents that are used to limit radioiodine emissions (Kovach 1980). However, it cannot be ruled out that during off-normal events the major form of radioiodine will be elemental. Therefore, evaluations of sample transmission under off-normal conditions should assume that form. Glissmeyer and Sehmel (1991) summarized the more recent studies on radioiodine sampling and transport and many of the following considerations are based on that summary.

C.2 Extraction and transport

The considerations for the extraction of gases and vapors set forth in clause 4.3 of this Standard are applicable to radioiodine. In view of the likelihood that at least some of the radioiodine in an air effluent will be attached to particulates, all of the considerations applicable to them as set forth in the main body of this Standard and its annexes also apply to the extraction and transport of radioiodine.

Laboratory studies have shown that in the extraction and transport of radioiodine, materials that contact the radionuclide may interact with it (e.g., copper, PVC, Buna-N). These materials should be avoided. Studies by Kabat (1983) indicate that the preferred materials are teflon, polyethylene, aluminum, carbon steel, and stainless steel.

Condensation of the iodine and water vapor in transport lines should be avoided by heat tracing the lines to at least 50°C (~120°F) and by avoiding abrupt temperature transitions.

The following equation (Glissmeyer and Sehmel 1991) relates the penetration at equilibrium, P, of radioiodine in transport lines to the so-called deposition velocity and parameters of the sampling system:

$$P = e^{-4 \frac{v_d}{U_m} \frac{L}{d_t}} \tag{C-1}$$

73

1 where: P is c_e/c_i;

2

3 c_e is outlet concentration;

4

5 c_i is inlet concentration;

6

7 v_d is dry deposition velocity;

8

9 U_m is average air velocity in transport line;

10

11 L is length of transport line;

12

13 d_t is diameter of transport line.

14

15 From this equation it is evident that the penetration of radioiodine vapor will be optimized by mini-
16 mizing the length of the transport line and using the largest diameter and the highest flow velocity
17 subject to external constraints (e.g., particle transport, space availability, or collector capacity).

18

19 Equation (C-1) does not take radioactive decay or resuspension into account. A model by Unrein
20 et al. (1985) gives an equilibrium relationship that includes these effects; namely:

21

$$P = \frac{1}{1 + V_d \left[\dfrac{\pi d_t L}{q} \right] \left[\dfrac{\lambda}{\lambda + r} \right]} \qquad\qquad (C-2)$$

22

23 where: r is resuspension rate, time^{-1};

24

25 λ is decay constant, time^{-1}.

26

27 Equation (C-2) suggests that the greater the resuspension rate, the larger the penetration. This is
28 also illustrated in figure C.1 where penetration is shown as a function of time and resuspension
29 rate. However, Glissmeyer and Sehmel (1991) indicate that resuspension rates of deposited
30 radioiodine, for each radioiodine species, decrease as a function of time. Resuspension rates are
31 also dependent on the amount of iodine initially deposited, of which some seems to remain firmly
32 deposited. The latter has not been directly observed by laboratory studies, but can be estimated on
33 the basis of an activity balance following prolonged observation. Finally, Glissmeyer and Sehmel
34 (1991) state there are no satisfactory experimental verifications of predicted penetration factors
35 under either equilibrium or transient conditions. However, the following generalizations can be
36 made from the limited available data, principally that of Unrein et al. (1985).

37

38 In a summary of sampling systems for reactors, Glissmeyer and Sehmel (1991) indicate that a
39 typical sampling system consists of a 15 mm diameter (5/8 in.) stainless steel transport line that is
40 about 52 m (170 ft) in length with a flowrate of about 57 liter/min (2 cfm). Simulated sample trans-
41 port lines with a range of similar designs were tested by Unrein et al. (1985) who measured short-
42 term (on the order of two hours) penetration factors of 0.62 for injected ^{131}I (as I_2) through 19 mm
43 (3/4 in.) diameter by 48 m (140 ft) long tubes. Glissmeyer and Sehmel (1991) predicted the
44 equilibrium penetration factor to be about 0.75, with an approximate time of two weeks to reach
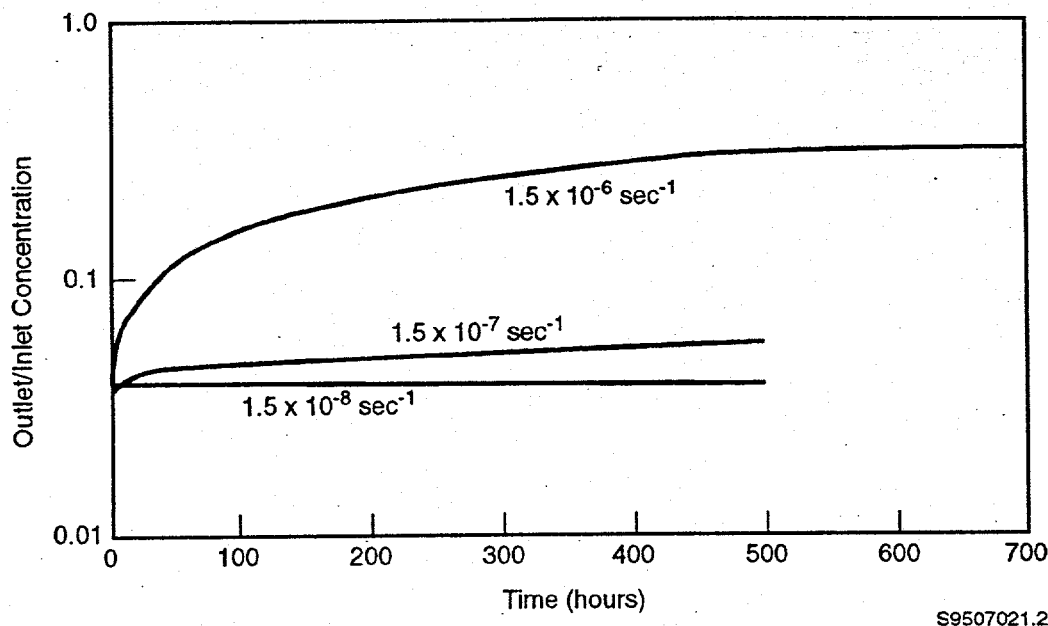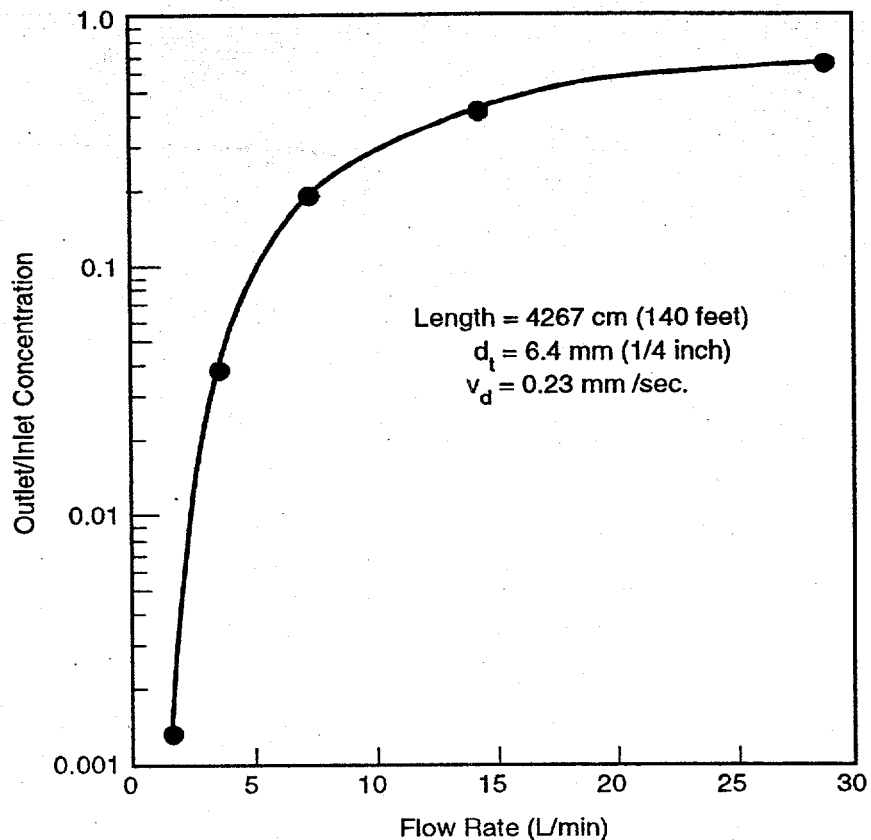45 equilibrium.

Figure C.1 — Predicted penetration of radioiodine as a
function of time for various resuspension rates

With the caveat that the penetration factor was not measured in the Unrein et al. (1985) tests until two hours after beginning iodine injection (lower penetration factors might have be found for measurements earlier in the test sequence), the above short-term results provide a conservative estimate of penetration factors following a step increase in radioiodine concentrations in conventional transport lines. The equilibrium value provides a conservative estimate for longer term sampling of normal concentrations.

Much smaller penetration factors were found for a few tests of systems with long transport lines of 6 mm (1/4 in.) diameter tubing when operated at flowrates of less than 1.7 liter/min (0.06 cfm).

Some accident air sampling systems used this design to reduce the potential dose at the sample collector by using a low sample flowrate and a small diameter transport line. Tests simulating such systems (Unrein et al. 1985) showed very poor penetration of the radioiodine to the collector. Consequently, many of these systems were redesigned to collect a low flowrate subsample from a high flow, large diameter transport line to take advantage of its favorable sample penetration from the stack. An example of the effect of flowrate on the penetration of I_2 in a small diameter transport line is shown in figure C.2.

The foregoing applies primarily to the transport of elemental radioiodine and, to a lesser extent, to the hypoiodous iodide form. Radioiodines in organic form, with their much lower deposition velocities, may be expected to be transported with higher efficiencies, thus making the above estimates additionally conservative. As summarized in Glissmeyer and Sehmel (1991), the fraction of organic radioiodine during normal operations appears to be quite variable from facility to facility, and there are no data on which to estimate the fraction that might be anticipated in the facility effluent during upset or accident conditions. Initially the predominant radioiodine forms during upset or accident conditions and will be elemental particulate.

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Length = 4267 cm (140 feet)
d_t = 6.4 mm (1/4 inch)
v_d = 0.23 mm /sec.

S9509031.3

Figure C.2 — Predicted initial radioiodine penetration through a stainless steel transport line. Tube size: 6.4 mm (1/4 in.) inside diameter by 43 m (140 ft) long.

C.3 Collection media for radioiodine

While carbon is an efficient collector of I_2, it is much less efficient for the low deposition velocity organic iodines. Kovach (1992) has indicated that the removal mechanism of elemental iodine on carbon adsorbents is primarily by physical absorption, the removal of hydrogen iodide (HOI) by physical absorption, chemical reaction and isotopic exchange, and that the removal of organic iodides such as CH_3I is by isotopic exchange. To improve the latter process, carbon filter media treated with potassium iodide (KI) or triethylene-diamine (TEDA) should be utilized. Packages with different types of adsorbents in series are available for the collection of radioiodine with separation by chemical form.

Annex D
(informative)

Illustration of criteria for optimizing the selection of
filters for sampling airborne radioactive particles

Table D.1 summarizes the type of information that is useful for selecting an appropriate filter for sampling airborne radioactive particles. The table includes a variety of coarse fiber, glass fiber, and membrane type filters, but does not constitute an endorsement of any particular manufacturer or filter type. Conversely, the absence of any particular filter from the example table does not consti- tute a rejection of that media. For general sampling applications, information is provided on durability, flow resistance, and efficiency. Information on collection of radon decay products and resolution for alpha spectroscopy is included for alpha continuous air monitor (CAM) applications. The alpha spectroscopy resolution is based on detection of the 6.0-MeV alpha emission of polonium-218 (a naturally-occurring decay product of ambient radon-222, which causes interference in instruments used to detect plutonium or uranium isotopes).

Filter efficiencies range from >99.999 at all particle sizes and flowrates for the Millipore type AA, 0.8 μm pore size membrane filter to <50% for the Whatman 41 cotton cellulose filter at low flow- rates and small particle sizes. Typical flowrates range from as low as 4 liter/min per cm^2 at 5 psig pressure drop for the Millipore Type AA membrane filter to as high as 59 liter/min per cm^2 for the Millipore Fluoropore, 5 μm pore size teflon membrane filter. Resolution for alpha spectroscopy of the polonium-218 alpha emission at 6.0 MeV ranges from as low as 350 keV (full width at half maximum) for the Fluoropore 3 μm teflon membrane filter to greater than 1500 keV for the Whatman 41 cotton cellulose fiber filter. The poor resolution associated with the Whatman 41 filter makes that filter unsuitable for detecting plutonium or uranium in the presence of ambient radon decay products. In addition, although the Whatman 41 is easily dissolved for chemical analyses, it has a collection efficiency that decreases dramatically at low flowrates. The Fluoropore filters have very low pressure drop, good collection efficiency, and excellent resolution for alpha spectroscopy, but are not readily dissolved for radiochemistry. Selection of the larger pore 5 μm Fluoropore filter over the 3 μm pore option provides a substantial improvement in flowrate, with only a modest decrease in sampling efficiency and resolution for alpha spectroscopy.

As new filter types become available, comparisons such as these can be made by the user to ensure that appropriate filter types are selected for sampling radioactive aerosols.

Table D.1 — Characteristics of filters evaluated for use in sampling radioactive particles (adapted from Hoover and Newton 1992)

Filter Type	Filter Composition and Durability	Typical Flow Rate (L/min per cm²)[a]	FWHM of the Po-218 PEAK (keV)[b]	Relative Radon Progeny Counts in the Pu ROI[c]	Relative Radon Progeny Collection Efficiency[d]	Filter Efficiency Range (%)[e]
Millipore Type SMWP (5.0 μm pore size). Millipore Corp., Bedford, MA	mixed esters of cellulose acetate and cellulose nitrate (fragile; electrostatic; both sides similar)	16	670	1	1	98.1 - > 99.99
Millipore Type AW19 (5.0 μm pore size). Millipore Corp.	homogeneous microporous polymers of cellulose esters formed around a cellulose web (rugged; both sides similar)	16	470	0.57	0.99 ± 0.01	
Durapore (5.0 μm pore size). Millipore Corp.	polyvinylidene fluoride (rugged; both sides similar)	14	790	1.55	0.67 ± 0.01	
Fluoropore (3.0 μm pore size). Millipore Corp.	polytetrafluoro-ethylene bonded to polypropylene high-density fibers (rugged; front is membrane; back is fibers; sides barely distinguishable by naked eye)	23	350	0.47	1.04 ± 0.02	98.2 - > 99.98
Fluoropore (5.0 μm pore size). Millipore Corp.	polytetrafluoro-ethylene bonded to polypropylene high-density fibers (rugged; front is membrane; back is fibers; sides distinguishable by naked eye - high contrast backing)	59	460	0.67	0.96 ± 0.04	98.3 - > 99.99

Filter	Description					
Versapor 3000 (3.0 μm pore size). Gelman Sciences, Ann Arbor, MI	acrylic copolymer on a nylon fiber support (rugged; both sides similar)	25	590	0.94	0.75 ± 0.02	-
Gelman Type A/E (~1.0 μm pore size). Gelman Sciences	borosilicate glass fiber without binder (breakable during handling; both sides similar)	25	≥ 1000	1.31	0.92 ± 0.01	99.6 -> 99.99
Whatman EPM 2000. Whatman LabSales, Hillsboro, OR	borosilicate glass microfiber without binder (breakable during handling; both sides similar)	20	≥ 1000	1.48	1.00 ± 0.03	-
Whatman 41. Whatman LabSales	cotton cellulose filter paper (rugged; currently used primarily for liquid filtration; both sides similar)	25	≥ 1500	1.65	0.42 ± 0.01	43 -> 99.5
Nuclepore, (0.6 μm pore size). VWR Scientific, Pleasanton, CA	polycarbonate membrane (rugged; thin; very electrostatic; currently used primarily for liquid filtration; collection side recommended by manufacturer is the shiny side)	4	500	0.89	0.85 ± 0.02	53 -> 99.5
Millipore Type AA (0.8 μm pore size). Millipore Corp.	mixed esters of cellulose (fragile; electrostatic; collection side is darker)	7	520	0.91	1.05 ± 0.01	99.999 -> 99.999

[a] Flowrate determined under vacuum at 35 kPa (5 psig).

[b] FWHM is the typical full width at half maximum of the Polonium-218 peak obtained with a 2.5-cm diameter filter and a 2.5-cm diameter solid state detector with a 0.5-cm separation distance during sampling of room air at the Inhalation Toxicology Research Institute in Albuquerque, NM.

[c] Radon progeny background counts in the Pu ROI for the filter of interest, divided by similar counts obtained simultaneously on a Millipore SMWP filter.

[d] Total radon progeny background counts on the filter of interest, divided by similar counts obtained simultaneously on a Millipore SMWP filter. Mean and standard error for five replicate tests.

[e] The range of filter efficiency values given generally correspond to a particle diameter range of 0.035 - 1 μm, a pressure drop of 1 - 30 cm Hg, and a face velocity range of 1 - 100 cm/s. Values are from Liu et al. (1983), except for the Fluoropore filters which are from Liu (1992).

Annex E
(informative)

Evaluating effluent sampling errors and uncertainty

E.1 Introduction

Error in the determination of a quantity such as the amount of radioactivity emitted from a stack during a certain period can be defined as the difference between its actual value (in some sense) and the measured value. Yet the real situations in which both the actual value and the measured value are known are typically those found when calibrating or qualifying a measurement procedure or instrument against standards, baseline data, or against one of the basic conservation laws of engineering. In most situations, it is the limits of uncertainty that might bound the possible errors that are quantifiable (Moffat 1988). Our understanding of the errors that contribute to the uncertainty in a measurement involve both fixed (bias) errors and random (precision) error. An estimate of the limits of uncertainty is required for a measurement that properly and completely combines both sources of error (ANSI/ASME PTC-19.1 - 1985).

The case of a simple stack effluent measurement system, such as a filter air sampler (FAS) connected by a transport line to a nozzle, will be used to illustrate a typical effluent measurement process. To estimate the amount of radioactivity emitted from a stack a sample of the effluent is extracted, transported to a collection medium, then collected. It is further necessary to quantify the collected material, then relate the quantified amount to the effluent. For the estimation of the effluent concentration it is necessary to know or estimate the effluent flowrate, the area of the sampling plane, the sample flowrate, the nozzle transmission, the mixing ratio of constituents in the duct, sample transport penetration, sample collection efficiency, and analysis efficiency.

The sampling and analysis processes contribute both fixed and random error to the overall uncertainty in the estimated radioactivity. In the case of the extraction plane parameters and instrument calibrations, both bias and precision errors are combined into one uncertainty carried into the operation phase. For example, during the calibration of the measurement devices, a known and constant input is presented and output or measured response is observed. Fixed errors are evidenced by offset of the mean value from the expected standard response, and variable errors by variation in the output. In other elements such as the nozzle inlet or transport line, calibration is not possible, but performance in tests with standard aerosols under known, controlled conditions can be conducted to establish bounds on expected performance. Similarly, uncertainty estimates can be put on parameters such as the area of the sample extraction plane, the degree of mixing of contaminants at the plane, and the mean axial velocity of effluent through that plane. Calibration removes part of the fixed error but not the uncertainty.

The fixed errors that remain embedded in the predetermined parameter or calibrated device elements are not fully known in a particular application. Bounds can be placed on the embedded errors. The random components of error arise during the calibration measurement processes. These are estimated by the standard deviation of the variable measurement component, such as the sample flowrate or the radioactivity in the sample. Such standard deviation estimates are derived from the data alone without external reference.

E.2 Contaminant transport uncertainty estimation

Regulatory limits on radionuclide emissions are generally stated in terms of limits on the resultant dose to members of the public per year. Thus a facility sampling and measurement system must generate an accurate and reliable estimate of quantities emitted in a given sampling interval that can then be input to an environmental transport and dose estimation model. The quantity of radioactive substances being transported out of a stack can be represented as:

$$E \approx c_A \, U_M \, A. \tag{E-1}$$

where: E is average radionuclide stack emission rate over the period of integration, Bq/s;

A is area of the sample extraction plane in the stack, m²;

c_A is effluent radionuclide concentration, Bq/m³;

U_M is mean axial effluent velocity in the stack, m/s.

The first term of equation (E-1), the effluent radioactivity concentration, is determined by radioactivity measurement, measured sample volume, and constant parameters of the system:

$$C_A = \frac{r_n}{Q \, P \, M_p \, \epsilon_f \, \epsilon_d} \tag{E-2}$$

where: r_n is net counts per minute (gross minus background) from the sample, cpm;

Q is volume of effluent that produced the sample at stream temperature, pressure, and gas composition, m³;

P is the overall penetration of sample from the free stream to the sample collection medium (combining transmission through the nozzle, T_p, and through the transport line, T_l): the ratio of concentration at the output of the sample transport line, to the effluent free stream concentration;

M_p is mixing of radioactive contaminant in the total effluent gas volume, determined as the ratio of the concentration in the sample volume to the concentration in the free stream, fraction.

ϵ_f is collection efficiency of the collection medium, fraction;

ϵ_d is detection efficiency, cpm/Bq.

The second term of equation (E-1), is the average effluent flow velocity, typically determined by preoperational measurements from traverses across the duct. Other methods and devices might be used such that near-real time data for U_M are developed.

Assuming that EPA Method 2 is used, the mean axial velocity of the effluent is computed from the results of multiple velocity determinations, one at each subsection of the traverse pattern over the

sampling plane. Once again, this determination is made during site qualification and subsequent verification, not during operational phases. The relation between U_M at a particular location, and actual parameters measured with a pitot tube is

$$U_M = U \cos(\theta) = C_P \cos(\theta) \sqrt{\Delta p / \rho} \tag{E-3}$$

where: C_P is pitot calibration factor;

Δp is differential pressure;

ρ_g is gas density, gm/cm^3. Gas density is determined from measured static pressure, molar mass of the gas, and temperature through the equation of state;

$U \cos(\theta)$ is measured velocity corrected for flow angularity at angle θ.

The last term of equation (E-1), the flow cross-sectional area A, will also have been predetermined from blueprints or from measurements across the stack or duct. That area is divided into sub-sections of equal area for purposes of measuring an average axial velocity.

Combining equations (E-1) and (E-2), the stack emission rate equation for $E_{average}$ (Bq/sec) is:

$$E_{average} = \frac{r_n \; C_P \; \cos\Theta \; \sqrt{\Delta p / \rho} \; A}{Q \; P \; M_p \; \epsilon_f \; \epsilon_d} \tag{E-4}$$

Equation (E-4) is the mathematical model of the emissions measurement.

E.3 Quantifying uncertainty

E.3.1 Stack emission measurement uncertainty analysis methods

An emission release rate is a function of a large number of measured parameters contained in equation (E-4). A basic analysis of uncertainty can be carried out under the assumption of near-normal distribution of random errors, which is valid for most, but not necessarily all of the variable parameters involved.

E.3.2 Overall uncertainty associated with the measurement process

An uncertainty analysis of explicit errors associated with measurement processes that take place either in the preoperational or operational phases has been developed. Each of the terms in the convective emission model have been examined, and expanded as appropriate. This is a recommended approach rather than attempting to write a single complex error equation. The total emission rate from the stack is calculated from radioactivity measurements on a continuous sample extracted from a qualified sampling location, and other measurements of parameters of the emission equation. The overall uncertainty in that number can be estimated by summing over each of the terms of an uncertainty equation (Moffat 1988).

E.3.3 Uncertainty associated with fixed errors

The several components of fixed uncertainty in an emission measurement can be combined in one term. An overall bias limit, B_L, defined as the maximum probable value of the total fixed error in the measurement estimated at the 95% confidence level, is the root-sum-square combination of all fixed error components. These can be classified as calibration bias, B_{CAL}, parameter estimate bias, B_{PAR}, and design and test bias for components such as nozzles and transport lines, B_{TST}:

— The calibration bias term, B_{CAL}, represents the fossilized overall calibration uncertainty, combining both elements of bias and random error, that accrue during calibration of instruments or devices. This is typically the residual bias remaining after gross bias is zeroed out (up to an acceptance limit) during calibration, and in some cases is identified by manufacturers as the accuracy limit of the calibrated scale or readout device.

— The parameter bias term, B_{PAR}, represents the overall uncertainty (again combining fixed and random error estimates) that derives from field and laboratory determinations of sample extraction parameters such as the degree of particulate mixing M_P or mean profile velocity U_q that ultimately are applied as a single value to estimations of stack emissions. Other fixed error contributions related to sampling location effects are treated separately below.

— The design and test bias term, B_{TST}, results from residual uncertainties in the process of design and qualification of sampling nozzles and devices that are engineered from first principles and empirical factors, and then manufactured and tested to confirm that certain performance characteristics, such as nozzle inlet penetration efficiency for 10 μm AD particles, have been met. Such a critical performance characteristic is specified by an acceptable range for a given set of operating conditions, and there is an acceptance limit on deviation between the design performance and the result of confirmation tests with tracer materials.

The overall bias limit then can be expressed as:

$$B_L = \left(\Sigma_i B_{CAL}^2 + \Sigma_i B_{PAR}^2 + \Sigma_i B_{TST}^2 \right)^{1/2} \tag{E-5}$$

where the summations are over the several contributions from devices or parameters contributing fossilized uncertainty to the measurement outcome.

The bias limit estimated at the 95% confidence limit serves the same purposes for the fixed error as does the two standard deviation random error estimate. It is combined with the 95% confidence limit estimate of the random error component in calculating the overall uncertainty of measurement. A full uncertainty analysis entails a careful consideration of the many sources of uncertainty and proper combining of each component to generate an overall uncertainty estimate.

The table 3 guidance levels for acceptable accuracy and precision of measurement require evaluation of factors that can contribute error to components of the system. Without detailed analysis, it may be difficult to demonstrate that estimates are reasonably complete and defensible. The discussion in the following sections is meant to provide a framework for an evaluation of uncertainty in effluent measurement based on an analytic expression relating radionuclide emission to variable parameters in the measurement, and on residual bias and implicit errors inherent in the methodology of continuous emission monitoring from a single point.

Recalling that the error in a measurement is defined as the difference between its true value and the measured value, it is worthwhile to reflect here on what interpretation should be given to the "true value" of measured effluent radioactivity emission rate by the single point representative sampling method. If we use the classification and nomenclature developed by Moffat (1988), the fact that flow and mixing parameters are averaged over the profile entails that the intended "true" emission rate is the "conceptual value" at the sampling location: the area-averaged emission rate of radioactivity from the stack based on single point sampling at the axial location of the single nozzle, assuming the installed instrumentation does not disturb either the concentration or the flow distributions, and that the preoperational measurements of critical parameters (i.e., U_M, P, Q, and Mp) properly reflect sampling under operational conditions. The conceptual value is to be distinguished from the "available value," which would be the emission rate estimated only at the axial location of the nozzle (without assumptions about disturbance, mixing, or how representative the parameter estimates are). Because we are interested in the well-mixed mean effluent radioactivity emission rates, the effects of velocity and contaminant maldistribution must be added to the list of sources of error, and uncertainties in the correction factors that account for the maldistribution must be considered. The estimation of the true emission rate (the conceptual value) depends on parameters measured at other times, under possibly different conditions, and with test aerosols and gases rather than the actual radioactive contaminants, so it is evident that the uncertainty in the result a single point sample depends on other considerations than explicit operational or preoperational measurement uncertainties.

E.3.4 Uncertainty associated with conceptual errors

As noted in clause 4.4, a useful distinction can be made between the errors of the measurement processes and those associated with the overall methodology. The measurement errors are attributable to explicit performance aspects of the sampling and analytic hardware. Sampling methodology errors derive from issues related to sample extraction location and related implicit factors that affect how well the sample represents the true emissions from the stack during the period of the sample. These are what Moffat (1988) terms "pattern factors" defined as factors that describe variation in velocity and mixing in the profile and an estimate of how the value of the emission rate at the nozzle location compares with the mean value. In some situations the conceptual errors can be the largest by far. Two of the more significant sorts of conceptual errors derive from assumptions about temporal variation and about the completeness and accuracy of model assumptions.

E.3.4.1 Errors associated with temporal variations

Changes over time in stream conditions following site qualification are assumed not to significantly influence the measurement outcome. Yet, increases or decreases in volumetric sample flow, effluent discharge rate, or modifications in the stack use can cause distortions in sample extraction or contaminant mixing. The degree of how representative a single point sample is could then change. That is why it is particularly important that whatever factors are counted upon to produce a well-mixed condition at a qualified sample extraction location should be robust with respect to reasonably anticipated changes in stack conditions. Mechanical mixing elements or deflected, colliding flows produce mixing conditions at the selected sample extraction plane that are less susceptible to change under modifications in facility use or under upset conditions, and so their use would support a lower estimated uncertainty δ_{TE}. A judgement will be required about assigning the significance of temporal variations and hence the magnitude of this uncertainty term.

E.3.4.2 Model errors, δ_{ME}

There are a number of simplifying model assumptions implicit in the representation of continuous emission monitoring by extractive sampling from a single point. Among these are that the contaminant transport processes in the sample nozzle and line are well represented by semi-empirical models in the DEPOSITION code or similar code, that the measured uniformity of the velocity profile and degree of mixing at the stage of site qualification will continue to apply during operations (a pattern assumption), and that the radioactivity measuring process is well represented by single parameter sample collection and radiation detection efficiencies. To varying degrees, model-based assumptions may not be fully correct for a particular application. Again, a judgement is required to assign an estimate to this uncertainty term. Both the temporal variation uncertainties and model errors can be combined with other fixed errors arising from various measurements in generating an overall bias limit estimate.

The user is advised to become very familiar with the assumptions and modeling limitations of the DEPOSITION code or any other code used to optimize sample transport line design to be sure that special concerns for deposition of highly reactive species, particle bounce or resuspension from previously deposited materials are properly accounted for. The same applies to models of other aspects of the sampling and measuring process. The use of computational modeling aids should be viewed as a part of a larger process of design and evaluation that should include data from laboratory studies, findings in the peer-reviewed literature, and field testing.

E.3.5 Describing the combined uncertainties in emission measurement

The last step of an uncertainty analysis is bringing together the 2σ random errors and the overall bias limit (equation E-1) into a combined estimate of overall uncertainty in the emission estimate:

$$E_{total\,(0.95)} = (B_L^2 + \Sigma_i\, 2S_i^2)^{1/2} \tag{E-6}$$

where: $E_{total\,(0.95)}$ is the estimated error limit of the effluent measurement at the 95% limit (ANSI/AME PTC 19.1-1985);

B_L is the expected upper limit of the total true bias error (the difference between the average of the total population and the true value, which is the true systematic or fixed error);

S_i is the sample standard deviation based on N measurements of the i-th term (precision index) for variable terms in the emission rate equation.

E.4 Evaluation of errors

Following Brooks (1979), estimates of the magnitude of most of the error terms can be described at least to the level of what is attainable at the 95% confidence level (corresponding to a $\pm 2\sigma$ interval for random variables). Many of the errors considered above are relatively small and controllable by good practice. Others require more careful consideration.

E.4.1 Errors in sample volume, stack area, and transmission efficiency

Errors in sample volume Q, and stack area A, are generally small and well understood. Sample volume measurement is readily accomplished and corrected for altitude and temperature. As described in clause 7, the accuracy of measurement of sample flow (and hence sample volume) with a flowmeter should be periodically checked with a secondary standard flowmeter, and differences maintained to less than 10% of standard (see clause 7, equation 11 for further details). 2σ random errors on the order of 5% should be achievable.

The cross-sectional area of the effluent flow at the sample extraction location should be accurately ascertained from engineering drawings of the effluent stack. Fixed errors associated with this determination should be much less than 2%.

Sample transport line penetration in the case of particulate effluent is harder to estimate because the characteristics of the aerosol being sampled cannot be fully described in advance. Although the particle size characteristics of many types of radioactive aerosols have been studied (see annex H for a discussion of such studies), many possibilities for HEPA filter failure and associated unique aerosol size distribution exist. Nonetheless, an estimate of the magnitude of error in this parameter can be made. First, the minimum acceptable transport line efficiency for 10 μm AED particles has been established at 50% (clause 6). It is expected that a proposed transport line for a sampling system would be designed for optimal performance using the DEPOSITION code (or equivalent) (annex B). The performance of the as-built system should be verified by laboratory testing with 10 μm monodisperse test particles if practicable. If in-stack field performance is estimated by simulating penetration of a characteristic polydisperse aerosol through the nozzle and line, then errors associated with the use of the predicted transport efficiency can be derived.

Consider for example the sample line described by Anand et al. (1993) in the DEPOSITION manual. It consists of a nozzle with a 0.2 m section feeding a 2 m horizontal tube through a 90° bend, followed by a 2 m horizontal tube connected to a vertical 2 m tube by a second 90° bend. For monodisperse 10 μm particles, the penetration is predicted by DEPOSITION to be 55.2%, which would qualify the system. Now assume there is a polydisperse log-normal distribution of particle sizes with an average activity median aerodynamic diameter (AMAD) of 1.8 μm and σ_g = 2.2, like that found in a research and development facility glovebox line by Ettinger et al. (1973). The DEPOSITION predicted penetration rises to 94.2%, a 70% increase. The user may assume the penetration of the system is the more realistic estimate for polydisperse aerosols rather than the conservative value based on 10 μm tracer tests, or make further field measurements with polydisperse test aerosols. For error analysis purposes, suppose the aerosol actually encountered in an accident effluent is more like a fabrication facility average size distribution (amad of 4.0 μm, σ_g = 1.7) reported by Ettinger et al. (1973). Then the penetration is predicted to be 85.9%, a relative difference of 8.8% compared with the 94.2% estimate. The average predicted deviation using a range of size distribution parameters from four other plutonium handling facilities included in their study is 7%. A 15% estimated 95% confidence level error relative to predicted performance assuming a realistic aerosol size distribution appears to be attainable. These estimates are summarized in table E.1.

E.4.2 Errors in velocity measurement parameters

Errors in the determination of velocity at each equal area location in a profile are summarized from Brooks (1979) in table E.2, assuming that an S-type pitot tube nozzle is used. Here, as in the case of the parameters of table E.1, attention to the details of the design and operation of the hardware in use is required.

Table E.1 — Errors in sample volume, stack area, and transmission line efficiency

Parameter	Error
Sample volume, $2\sigma_Q/Q \times 100\%$	± 5%
Stack area, $2\delta_A/A \times 100\%$	± 2%
Transmission line efficiency, $2\delta_{Tp}/T_P \times 100\%$	± 15%

Table E.2 — Velocity measurement parameter errors

Parameter	Error
Pitot calibration: $2\delta_{Cp}/C_p \times 100\%$	± 1%
Flow angularity: $2\tan(\theta)\delta_\theta \times 100\%$	± 8%
Differential pressure: $2\delta_{\Delta p}/\Delta p \times 100\%$	± 14%

E.4.3 Errors in radioactivity measurement parameters

Measurement of radioactivity in a sample can either be an on-line process in a continuous monitor, or off-line process in a laboratory. In either system, detector efficiency and sample capture efficiency parameters can usually be well defined. Detector efficiency is typically determined by comparison against a transfer standard traceable to NIST. Fixed errors can be held to a minimum (1-2%).

Poisson errors in the radioactivity counting process and random errors associated with background interference variability are the largest contributors to this error parameter. However, bounds can be put on these errors by careful planning.

In most circumstances a relative 95% confidence level error of 5-10% appears to be attainable by adjustment of sample and background count times. But this may not always be possible due to unrealistically long count intervals that will result.

E.4.4 Methodological errors

Turning now to the implicit methodological or conceptual uncertainties, there is a large component of engineering judgment required to assign values to these, but bounds can be placed on the estimated uncertainty.

The representativeness of the sample withdrawal location, for example, can be estimated by the measured coefficient of variations in mixing of tracer gas and tracer particles that are required as part of qualifying a sample extraction location for continuous emission single point sampling and monitoring. Based on limited studies, it appears that a 95% confidence limit error of $\delta_{RE} = 10\%$ is attainable, and in any event should be much less than 20%.

Random errors associated with changes in effluent emission conditions over time are difficult to predict. If mixing elements installed in a stack are employed to assure complete mixing, then an estimate of the 95% confidence limit on uncertainty due to time varying effects on the order of $\delta_{TE} = 2 - 4\%$ appears to be reasonable.

Similarly, model assumption uncertainty, at the 95% confidence level, on the order of $\delta_{ME} = 2 - 4\%$ are feasible as long as proper qualifications of the sampling nozzle, sample transport line, and sample withdrawal location are demonstrated.

E.5 Summary of error analysis

Estimated uncertainties in tables E.1 and E.2 (or equivalent from an independent analysis) and the other parameter uncertainty estimates can be substituted into appropriate equations to obtain a total explicit measurement process uncertainty estimate. The estimated radioactivity measurement error term (5.5%), sample volume measurement error (5%), and sampling plane area uncertainty (1%) contribute least to the total. Sample transport line efficiency uncertainty (15%) and emission mean axial velocity uncertainty (10.7%) terms contribute most. The resultant combined uncertainty is on the order of 19%.

Combined with the conceptual uncertainty estimates, the overall effluent radioactivity measurement uncertainty estimate is:

$$E_{total\ (0.95)} = \pm \sqrt{(0.19)^2 + (0.07)^2 + (0.02)^2 + (0.02)^2} \times 100\% = \pm 20\% \qquad (E-7)$$

This estimate should be understood as an indication of what might be attainable based on the assumptions concerning the measurement procedures carried through the analysis. Differences in the way mean axial velocity is determined, improvements in reducing errors in volumetric flow measurement, and better potential transport line loss estimation could be made in some cases, as could reductions in uncertainty in certain of the profile "pattern" parameters such as any of the statistics describing mixing at the sampling plane.

E.6 Correlated errors

The analysis to this point has been under the assumption that the errors are separable. The errors are not separable in all cases. The transport efficiency, T_s, and the collection efficiency, ϵ_f, are dependent upon the flowrate. In some cases, the detection efficiency is dependent on the flowrate.

Based on the uncertainty analysis of E.4 it may be concluded that the flowrate uncertainty is ignorable. Flowrate uncertainty may be ignorable based on its intrinsic uncertainty, but not on its extrinsic or correlated uncertainty.

The transport penetration is dependent upon the flowrate. If high transport penetration (>90%) is the case for all particle sizes, flowrate changes of 10% or less may have little effect on the transport efficiency. When the transport penetration is lower, small changes in the flowrate may greatly effect the transport efficiency for some particles sizes. These changes should be empirically determined or calculated using a code such as DEPOSITION. A similar relationship for particle collection can be developed. The same correlated uncertainty arguments pertain.

1　The detection efficiency can be affected by the flowrate if detection is dependent upon geometry
2　and the geometry is collection dependent. A simple example is alpha particle detection on a filter.
3　If collection of large, high activity particles takes place primarily near the edge of the filter and,
4　therefore, the edge of the detector, then detection efficiency for these particles will be diminished.
5　The flowrate correlated uncertainty should be determined.
6
7　Flowrate correlated uncertainties in these cases are further dependent upon the particle size distri-
8　bution, i.e., on a few large particles may have little effect, while a dominance of large particles may
9　have dominant uncertainties.

Annex F
(informative)

Sampling system performance verification

F.1 When to conduct sampling system performance verification

There are instances when a performance verification of a sampling system is advisable. These include:

— before a new system becomes operational;

— an existing system which has just come under additional regulatory requirements;

— an existing system where the potential to emit contaminants has changed significantly;

— an existing system where there have been significant changes, for example: changing the stream flow beyond the original design limits, adding a new effluent stream in a manner that destroys the well mixed state at the nozzle location, or changing system operating parameters outside of the design range;

— when the supporting documentation for a newly installed system is deficient.

F.2 Approaches to verification

The methods for verifying sample transmission performance through nozzles and transport systems fall into four categories:

— in-place testing;

— laboratory simulations;

— modeling based on deposition and resuspension rates determined in the laboratory;

— a combination of the above.

Table 4 of this Standard summarizes the requirements for qualifying sample extraction locations, nozzles and transport lines for particles, gases and vapors. Clause 6.2.2 requires that nozzle performance for particles be tested with a liquid aerosol. Clause 6.3.1 requires that transport line performance also be assessed in the same way or with a verified model. Clauses 5.2 and 5.3 state methods to be used for qualifying the sampling location for particles, gases and vapors using in-place testing. Nozzle and transport line performance methods for gases and vapors are not specified in the standard.

Meeting the performance requirements will usually involve a combination of methods. In-place testing may give the most unambiguous result, but may also be difficult to implement in all situations. The following sections give examples of methods in each category.

F.3 In place testing

F.3.1 Particle sampling examples

Rodgers et al. (1994) provides the most recent example of employing the methods outlined in clauses 5 and 6. Sulfur hexafluoride gas and oleic acid aerosols were the tracers used to qualify the sample extraction location. The oleic acid aerosol was also used to verify the performance of nozzles and transport lines for particles. Other verification examples include the following:

— Leuba and Schwabacher (1961) used 3-30 μm aluminum and iron powder aerosols;

— Schappel (1961) used uranium aerosols;

— Ström and Hesböl (1977) used fluorescent dye-tagged dioctyl-phthalate 20 μm aerosol;

— Curtis and Guest (1986) used submicrometer sodium fluorescein dye aerosol;

— SAIC (1991) performed tests on several stacks using polystyrene latex microspheres and optical particle counters sampling from the nozzle inlets and the exits of the transport lines;

— Newton et al. (1983) conducted tests of the sampling systems at the Waste Isolation Pilot Plant using salt aerosols;

— Glissmeyer (1992) tested systems using powdered tracer aerosols with geometric mean diameters of 1.3 μm and 8.5 μm. Temporary sample collectors were arrayed across the stack to characterize the mixing and to determine the average emission rate for comparison against the existing system;

— Kenoyer (1993) used cascade impactors and optical particle counters in tests of several systems without employing tracer aerosols.

F.3.2 Radioiodine sampling examples

Ström and Hesböl (1977) tested sampler performance for radioiodine by injecting both depositing and nondepositing forms of iodine into the ventilation stream. Samples were collected both in the stack at the elevation of the sampler nozzles and at the regular sample collection point. The non-depositing form was ^{131}I-tagged methyl iodide and ^{131}I$_2$ was used as the depositing form.

Curtis and Guest (1986) used stable methyl iodide and elemental iodine injected into the stack flow upstream of the fan. Collected iodine samples were analyzed using neutron activation.

Leuba and Schwabacher (1961) used ^{131}I injected into a stack which was sampled at several locations in the cross section using charcoal traps. Together with velocity data and tracer aerosol tests, the contaminant profiles for the stack were obtained.

F.4 Laboratory simulation

Laboratory simulations are more rapid and convenient than in-place tests. It is unlikely that complete systems can be simulated and the effects of surface contaminants in older systems may significantly effect real performance.

F.4.1 Particle examples

SAIC (1991) conducted a test of a full scale sampling system of simple design. The tests were conducted using polystyrene latex microspheres laser particle counters sampling from the nozzle inlet and from the end of the transport line. McFarland et al. (1991) conducted tests of a simulated sampling system using sodium fluorescein tagged oleic acid aerosol.

F.4.2 Radioiodine examples

Unrein et al. (1985) and Edson et al. (1987) conducted radioiodine line-loss tests to simulate air samplers used at several nuclear generating stations. The tests cover the range of air sampler characteristics commonly observed at reactor sites. The sample transport tubes were either 304 or 316 stainless steel as clean as received from the distributor. The results from these and other tests were summarized by Glissmeyer and Sehmel (1991).

F.5 Modeling

Modeling is often used to address the performance of transport lines. Modeling does not completely address all performance aspects of a sampling system, notably the adequacy of contaminant mixing at the sampling plane. This weakness may be overcome in the future as illustrated by Gielow and McNamee (1993) who used a three-dimensional fluid mechanics model to identify potential flow measurement locations in a power station offgas ductwork. They also compared model results against velocity traverse data.

F.5.1 Particle examples

Fan et al. (1992) provides an example of the use of the DEPOSITION code and compares the results against tests of a simulated air sampling system. Examples of the use of earlier models include:

— Rodgers (1987);

— Alvarez et al. (1985);

— Schwendiman et al. (1975).

Annex B describes most of the elements that need to be taken into account in a particle loss model.

F.5.2 Radioiodine examples

SAIC (1991) modeled the radioiodine transmission through several sampler transport lines. Other examples are summarized by Glissmeyer and Sehmel (1991). (See also annex C.)

Annex G
(informative)

**Transuranic aerosol particulate characteristics: implications
for extractive sampling in nuclear facility effluents**

G.1 Introduction

The engineering of stack monitoring and sampling systems for nuclear facilities requires close attention to the design and placement of the sample extraction nozzle and transport line to assure the most representative sample possible (McFarland and Rodgers 1993). With respect to the physical characteristics of the effluent that would have to be sampled under normal and especially emergency conditions, little has been said other than that the most significant accident in a facility in terms of both an event and an interacting agent is likely to be fire (Corely and Corbit 1983). The fire can cause radioactivity sources to release airborne radioactive aerosols, and the smoke can plug filtration systems causing the filter to lose its integrity by rupture of the medium or seals. Therefore, there are no definite answers concerning the aerosol characteristics that a sampling nozzle and transport line should be capable of handling. However, a number of investigations have been made of the expected filtration performance of HEPA filters under standard operating conditions. For the fire accident condition, a number of investigations have been made of the characteristics of aerosols present in glovebox confinement or generated when containment structures, flammable liquids, and commingled radioactive materials are spilled and burned. Because these aerosols would be expected to be present and challenge filters in a fire, they provide a first approximation of the character of aerosols that would have to be sampled in effluent stacks. The following discussion is meant to place some reasonable bounds on the size of particles that would typically be present in the event containment is lost and to provide some perspective on the type of design and testing considerations to be applied to sampling nozzles and transport lines.

G.2 HEPA filtration effects

Nuclear facility stack emissions are typically controlled by multiple levels of HEPA filtration. The HEPA filter is designed to remove particulates from a gas stream with an efficiency of at least 99.97%. Selective penetration of HEPA filters by submicrometer size particles (d_p = 0.1 - 0.4 μm) is predicted by filtration theory (Scripsick 1994). Some have been tempted to conclude (Nininger and Osborne 1992) that for this reason, it is not necessary to design nozzles for HEPA filtered stacks that take into account inertial effects in the sampling nozzle inlet and transport line. In their studies at the Rocky Flats Plant of particulate emissions in stack effluents, Ninninger and Osborne (1992) sampled for particles downstream of HEPA filters in an attempt to demonstrate the absence of large particles. A laser particle counter was employed to obtain data on numbers of particles in several size bins from submicrometer to over 10 μm (physical diameter). Based on particle *count*, there was observed to be only a small fractional percentage of particle counts corresponding to diameters greater than 5 μm, but when these data of counts per diameter bin are converted to *volume* distribution (hence reflecting the actual distribution of mass and radioactivity in the samples rather than number of particles) the volume percentages corresponding to particles with diameters greater than 5 μm are quite significant (greater than 30%). Further, recent studies by Scripsick (1994) of leak phenomena in HEPA filters have shown that by a variety of mechanisms (pinhole leaks, frame seal leaks, etc.), larger size particles can and will penetrate HEPA filters, which would explain the Ninninger and Osborne findings. For example, where filtration theory predicts a penetration fraction of 10^{-20} for 1μm particles, the observed penetration is approximately 10^{-5}.

1 Scripsick concludes that the size distribution of particles penetrating HEPA filters is primarily
2 determined by the size distribution of the challenge aerosol and not the media in the filter unit. This
3 is consistent with studies of multiple HEPA banks by Ettinger et al. (1973), whose data are
4 summarized in table G.1.

6 Here the presence of a small but significant fraction of supra-micrometer sized particles beyond the
7 second and third stage is indicated because the geometric standard deviations remain large. But the
8 respective activity concentrations are very small due to the reduced challenge and narrowing spec-
9 trum of particle size at each successive stage. At the same time, failure of earlier stages would be
10 expected to result in both higher release concentrations and larger quantities of particles in the
11 inertial size range (1 μm AD and larger). Therefore, the design of extractive sampling systems in
12 HEPA filtered stacks should reflect consideration of the presence of large particles, even under the
13 presumption of normal operating conditions and HEPA filtration.

G.3 Transuranic aerosol characteristics under accident conditions

18 HEPA filter failure under a variety of accident conditions adds another dimension to the concern for
19 being prepared to sample particulate radioactivity in larger size ranges. But now we must ask, if
20 substantial HEPA failure occurs, what is the upper bound of particle size that one could expect to
21 have to sample efficiently in order to properly represent the majority of the activity in the effluent?
22 In other words, would the effluent aerosol at the sampling plane suddenly shift to one characterized
23 by the occurrence of a significant particle size mode in a region beyond 10-15 μm AD? It is under-
24 standably difficult to characterize aerosols expected to be associated with HEPA failure. As is the
25 case with normal, intact HEPA filter banks the characteristics of the aerosol penetrating a failed
26 HEPA will be determined by the characteristics of the challenge aerosol. The literature derived from
27 studies of aerosols associated with accidental spills and fires in nuclear facilities, and of *in situ*
28 dusts and debris in uranium/plutonium gloveboxes and ducts, provides the best indications of what
29 to expect. The following synopses of a few cases are indicative of what is known and expected:

31 1) In a study of plutonium particle sizes in air samples taken in operational areas at the Rocky
32 Flats Plant many years ago, when maintenance operations on gloveboxes resulted in loss of
33 containment (Kirchner 1986), operations such as machining, oxide crushing, and fluorination of

Table G.1 — HEPA efficiency and particle penetration of Pu aerosols

HEPA stage	Particle size AMAD[a] of challenge μm	Mean measured efficiency %	Remaining activity dpm/m^3 [b]
1	0.7 - 2.1 $\sigma_g = 2 - 3$	99.99876	$10^5 - 10^6$
2	0.45 - 0.82, $\sigma_g = 1.5 - 2$	99.99817	$10 - 10^2$
3	0.37 - 0.70 $\sigma_g = 1.3 - 1.8$	99.86492	0.01 - 0.05

[a] AMAD = Activity mean aerodynamic diameter.
[b] Challenge aerosol concentration $10^{10} - 10^{12}$ dpm/m^3.

plutonium were found to produce airborne particles with mass median aerodynamic diameters (MMAD) of 2-4.5 μm (assumed density of 11.45 gm/cm^3). Conditions related to glove failure on a plutonium metal burning box leading to worker exposure produced larger airborne particles having a MMAD of 13.8 μm. Kirchner noted that these data agree very closely with the activity median diameters (AMAD) of particles measured at the AERE radiochemical laboratories in Harwell, England by Sherwood and Stevens (1965).

2) Ettinger, Elder, and Gonzales (1973) placed sampling nozzles in process lines or gloveboxes under "worst normal" conditions (i.e., when aerosol generation as a result of routine operations was highest) in a study of challenge aerosol characteristics and the response of multiple HEPA filters. Facility operations included research and development activities, fabrication, and chemical recovery. Activity concentrations in challenge aerosols were in the range of 10^6 to 10^7 dpm/m^3. Fabrication operations produced fairly large aerosol particles (predominant AMAD of 3-5 μm AD), while recovery operations consistently produced particles in the submicron range (0.1-1.0 μm). Research and development operations generated particles predominantly in the intermediate range (1-4 μm). The largest reported size bin in the log-normally distributed impactor data from all sites was a 10.9 μm bin (normalized frequency of 4% by activity), from a research and development facility.

3) When accidental events are considered, the potential contribution of fire generated aerosols should be included. In Pacific Northwest Laboratory studies of burning radioactively contaminated materials (Halverson et al. 1987) uranium was a surrogate for plutonium. Combustion aerosols containing uranium from contaminated plastics produced fairly large particles (1-5 μm MMD). Compounds in glovebox gloves (polychloroprene) produced the largest particles (19.9 μm MMD). Burning cellulose produced a wide range from <1 μm to as large as 10.5 μm MMD. Conversion of these numbers to aerodynamic diameter is uncertain due to unknown density and shape factors.

4) Accident conditions may involve leaks or spills of liquid and powder forms of radioactivity leading to airborne materials. In studies with uranium and other surrogates, Ballinger et al. (1988) measured particle MMDs in a wide range of between 3 and 20 μm MMD. Liquid spills appear to produce the largest particles from splash droplets that start large but get smaller as the liquid evaporates. Powder spills have more variability in particle size due to agglomeration effects in the bulk state.

5) Agglomeration in accident generated aerosols have been shown to produce larger particles in a polydisperse aerosol of smaller particles. However, it would appear that this process does not yield extraordinarily large modes of particle size. Using data from ORNL's nuclear safety pilot plant experiments with burning sodium in a containment structure, Jordan (1986) predicted (and confirmed with observation) relatively stable mean aerodynamic diameter time behavior. Diameters remained below 5 μm AD for 5 days following release and confinement.

6) In some DOE facilities there is the potential for involvement of plutonium metal in fire scenarios. Studies have been made of the release of aerosols under reducing and oxidizing environments. Edison et al. (1988), for example, found that activity median diameters of plutonium aerosols generated from plutonium metal pellets and foils were variable, but ranged from 4 to approximately 10 μm AD.

G.4 Implications for nozzle design

The available data indicate that the most common mode of particle size for plutonium and uranium aerosols under a wide variety of conditions of generation is between 1 and 5 μm AD with measurable percentages of particles at 10μm, or up to 20 μm. The appearance of particles in the inertial size range (above 1 μm AD) can be anticipated even under routine operating conditions and certainly under a wide range of accident conditions. Inlets of sampling nozzles for particulate emissions should then be tested for transmission performance in the range of 3-15 μm. The shrouded nozzle inlet, for example, is designed so that transmission of inertial size particles through the inlet is between 83% and 103% under flow conditions of intended use. Predicted performance of a design is confirmed with measurements in an aerosol wind tunnel using 10 μm AD test aerosols. The design is iterated until there is good agreement between predicted and measured performance, at which point the shrouded nozzle is qualified for use. Unless it is known that a facility stack effluent could contain a sizeable mode of very large size particles due to the nature of the materials being handled, it would not necessary to require performance testing into size ranges beyond 15 μm.

G.5 Implications for other nuclear facilities

Although the foregoing discussion has relied largely on data from plutonium facility experience, the concern for proper sampling and monitoring of large particle components of effluents downstream of HEPA filtration in other types of nuclear facilities is equally important. In their review of a wide range of literature on particle size distributions of radioactive aerosols measured in workplaces throughout the nuclear industry and government laboratories, Dorrian and Bailey (1995) found that in a total of 52 papers reporting 160 measurements of particle AMAD, the measurements of AMAD in the nuclear power industry and fuel handling facilities follow similar distributions to those in workplaces as a whole, with median values of about 4 μm. The exception seems to be uranium mills where the median is about 7 μm. The implication is clearly that the challenge aerosols presented to HEPA filtration in stacks and ducts in practically any nuclear facility will contain a significant component of particles larger than 2 to 3 μm AD, and thus could be present downstream of the filtration banks where sample extraction takes place.

Ström (1989) reviewed the characteristics of accident generated aerosols in Swedish power reactors. A large body of literature exists on aerosols, vapors, and gases generated in postulated power reactor accidents. Little is available concerning less consequential off-normal events.

Annex H
(informative)

Tritium sampling and detection

H.1 Tritium chemistry

Tritium, an isotope of hydrogen, generally behaves in a manner similar hydrogen. Typically it is found in two primary forms in the exhaust stream, 1) in the elemental form as a gas or 2) in the oxide form as water vapor. It is of particular interest that tritium in the oxide form has a boiling point slightly greater than 100°C. (For some regulatory analysis this would allow the oxide form to be considered a liquid instead of a gas, which would allow the use of a liquid physical form factor instead of that for a gas.)

Also, tritium is sometimes found in the exhaust stream as a component of methane or other volatile organic, or as a component of particulate matter. One such example is LiOH, where the hydrogen is replaced with a tritium molecule (LiOT). This compound is a solid material at temperatures over 400°C.

H.2 Sampling considerations

The first step in selecting an appropriate sampling system is determine the chemical form of tritium in the exhaust stream. If it is present in multiple forms, multiple sampling techniques may be employed. When the oxide form is present, the temperature and moisture content of the exhaust stream must be carefully considered. If the exhaust stream contains water in droplet form, then the tritium may also be in this form and sampling as though particles were present is recommended. Sampling for a vapor only is appropriate when the oxide is not be expected to condense.

H.2.1 Sample nozzle

The sampler nozzle should be located in the appropriate place depending on the chemical form of tritium. The location and nozzle configuration should conform to practices outlined elsewhere in this guide.

H.2.2 Heat tracing

The use of heat tracing on sample lines designed for tritium sampling should be evaluated very carefully. Several of the tritium sample collection methods rely on either absorption of water vapor into a media or condensation in a condenser apparatus. If the temperature of the sample is maintained too high, the tritium will desorb from the media, not all of the vapor will condense, and some of the absorbing solution in bubblers could be lost. All of these conditions will result in biased results.

On the other hand, if the physical state of the tritium in the exhaust is gaseous or vaporous, and the exhaust stream contains high humidity, then heat tracing may be needed to avoid condensation of sample in the sample lines and sample chamber. Condensation could cause the sample collector to plug and in the case of an ionization chamber, the reading could be disrupted because of shorting the central electrode to ground or the high voltage electrode.

H.2.3 Media location

Except for tritium existing in a particulate form, the tritium sample media is generally located downstream of a particulate filter. This keeps particles from plugging the sample media.

H.3 Sample Media

There are several generally acceptable methods and/or media available for sampling tritium when it is not in the particulate form. When it is in the particulate form, then sampling methods for particulate matter discussed elsewhere in this guide should be used.

Although there are many factors that affect the sensitivity of a method, sensitivities on the order of 1 pCi/ml are possible with sampling followed by laboratory analysis. Typical factors, but certainly not all possible factors, that can affect sensitivity are sample flowrate, temperature of sampling, pressure of sampling, analytical method, and sample media.

Often, information on the concentrations of both the oxide and elemental gas forms of tritium is desired. The uptake from tritium in the oxide form is very efficient, on the order of 99% (NCRP 62, 1979); however, only 0.004% of the elemental tritium entering the body is converted to the oxide form and adsorbed. Therefore, releases of tritium in the elemental form will have a much lower dose threat than that from the same quantity of tritium oxide. Combinations of the following methods can be used to determine total tritium and oxide levels, with the difference being the elemental tritium in the stream being sampled. Direct measurement is also possible by first removing the tritium oxide, then converting the elemental tritium to an oxide form, followed by additional sampling.

H.3.1 Silica gel

This method of sampling tritium oxide is the simplest to perform. This is a continuous sample collected over a period of days to weeks. It involves placing a canister of silica gel in the sample stream and absorbing the tritium as water vapor on the silica gel. Indicating silica gel, which is one shade of blue when fresh and either another shade of blue or a completely different color after it absorbs moisture, can be used for sampling tritium oxide. Once the sample is collected it is sent to a laboratory where it is heated to desorb the tritiated water.

If tritium in the elemental form is present, then a catalyst, such as palladium, can be installed upstream of the sample chamber. The catalyst converts the elemental tritium to the oxide form which can be absorbed on the silica gel.

H.3.2 Molecular sieves

This method is identical to the silica gel method, except molecular sieves are used in place of silica gel. This method has a two advantages over silica gel: 1) the media can be better dried initially, resulting in a lower background and 2) a palladium catalyst, which converts the elemental tritium to the oxide form, can be coated directly on the molecular sieve. A primary drawback of molecular sieves is desorption of the tritium. This typically involves heating the media to 500°C in an evacuated furnace. Also, molecular sieves have a lower moisture handling capacity than silica gel, but the media is a more efficient drier. Therefore, when the moisture content of the sampled exhaust is high, silica gel is probably a better media. However when the moisture content is low, molecular sieves may be a better choice.

H.3.2 Bubblers

Although a variety of absorbing materials can be used in bubblers, the most common is ethylene glycol. This method provides advantages to the laboratory, in that sample desorption is not required. The primary disadvantage is that the liquid media and bubblers are typically glass, and they must be handled in the field or plant environment.

H.3.4 Condensation

In high moisture exhaust streams condensation may be the method of choice, since the other methods are limited by exhaustion of the absorption media; however, this method can be difficult to use. This method is based on the condensation of tritiated water with a dehumidifier or condenser. The sample is routed through a mechanical cooling system and the condensate is collected in the liquid state. A loss or reduction of cooling capacity of the condenser will allow tritium containing moisture to leave the system in the exit gas. To ensure representative sampling, regular equipment maintenance is required.

H.3.5 Catalysts

All of the above methods rely on the tritium being in a vapor form, generally water vapor. When tritium is present as an elemental gas, then it must be converted, using a catalyst, to the oxide form before it can be sampled. Although any catalyst that will convert elemental hydrogen into the water or oxide form could be used, a palladium catalyst is the most common choice.

When tritium is present as an organic chemical species, a combustion catalyst must often be used. An example is a platinum on aluminum oxide catalyst in a heated combustion chamber. The tritium in the organic compound is oxidized to HTO and collected using the methods described above.

H.4 On-line detection

H.4.1 Ionization detectors

This is a very simple detector that will detect both elemental and oxide forms of tritium. The sensitivity can be as low as 10 pCi/ml depending on chamber volume. The major draw back to this detector is that it is sensitive to any gamma field in the general area and to any other ionization occurring in the chamber. A second chamber is sometimes use to compensate for external gamma fields by exposing the second chamber only to the field and not the exhaust stream. An additional chamber with a silica gel or molecular sieve pretreatment is sometimes used to discriminate between oxide and elemental tritium.

This type of detector can be used when tritium is present in organic vapors, such as tritiated methane.

H.4.2 Proportional counters

This type of counter detects tritium by using a rise-time discrimination principle. Since the soft beta of tritium has a short drift time this detector can discriminate between tritium and other radionuclides such as noble gases or other gamma emitters. The sensitivity of these instruments is on the order of 0.01 pCi/ml.

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2   (informative)
3
4   **Bibliography**
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